TECHNICAL NOTE

D-1303

APPROXIMATIONS FOR THE THERMODYNAMIC AND TRANSPORT

PROPERTIES OF HIGH-TEMPERATURE NITROGEN

WITH SHOCK-TUBE APPLICATIONS

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SUMMARY

Approximate thermodynamic and transport properties of equilibrium nitrogen have been calculated over a range of temperatures and pressures from $293°$ to $30,000°$ K and 10^{-4} to 10^3 atmospheres. Three reactions, dissociation, single ionization, and double ionization, have been considered for this range. These nitrogen properties were found to approximate the behavior of air properties in the region where double ionization of nitrogen and oxygen atoms occurs. The thermodynamic properties of nitrogen were also used to calculate the pressure, temperature, density, and enthalpy behind incident and reflected shock waves. These shock-wave relations were used in conjunction with shock-tube experiments to determine the integral of thermal conductivity up to a temperature of $6,000°$ K (region of dissociation). A comparison of the experimental and calculated interface temperature rises and integrals of thermal conductivity showed rather good agreement. The close correlation indicates that the predicted thermodynamic properties and coefficients of thermal conductivity are sufficiently accurate for some engineering needs up to the limits of the test $(6,000°$ K).

INTRODUCTION

To predict the aerodynamics and heating of high-speed vehicles entering planetary atmospheres, the thermodynamic and transport properties of gases at high temperatures must be known. Approximations for the thermodynamic and transport properties of high-temperature air exist for orbital and reentry calculations (refs. 1 to 4). A logical extension of the space program is the attempt to reach the planets nearest the Earth, Venus and Mars. The prediction of the entry characteristics for these two planets requires a knowledge of the properties of the constituent gases. Astronomical observers are of the opinion that the atmosphere of Mars is composed almost entirely of diatomic nitrogen with traces of carbon dioxide (refs. 5 to 7). Until recently, the opinion was also held that the atmosphere of Venus was composed of a large percentage of

carbon dioxide with a smaller percentage of diatomic nitrogen (refs. 6 to 8). However, Kopal in his interpretation of the available spectroscopic and photometric data has predicted an atmospheric model for Venus which is predominately nitrogen (ref. 9). In any case, the necessity for determining the thermodynamic and transport properties exists. These properties may also be used in the calculation of other aerodynamic and thermal problems within the terrestrial atmosphere, since it seems probable that the behavior of nitrogen is representative of the behavior of air in a large range of temperatures and pressures where little data for air are available.

In this paper the approximate thermodynamic and transport properties of high-temperature nitrogen are calculated and the thermodynamic properties are applied to the calculation of shock-wave properties. The results of these two calculations are then used in conjunction with shock-tube experiments to determine the integral of thermal conductivity of nitrogen. The underlying theories and assumptions used have been developed by Hansen, et al., in reference 4 (properties of high-temperature air), reference 10 (shock-wave properties), and references 11 and 12 (integral of thermal conductivity for air). In the following development, these underlying theories and assumptions will not be repeated. Only the pertinent equations plus a few guiding remarks will be given.

The equilibrium thermodynamic properties are calculated from quantum statistical thermodynamics, with the aid of spectroscopically determined energy levels of nitrogen in the molecular, atomic, and ionic forms. The transport properties are based on the simple binary collision model of kinetic theory. The more rigorous methods of Chapman and Enskog (refs. 13 and 14) were not used because of insufficient knowledge of intermolecular potentials. The incident and reflected shock-wave relations are based on the familiar conservation equations of fluid mechanics. The degree of approximation in the various theories is discussed in references 4 and 10.

The purpose of the present paper is to provide an engineering approximation for the properties of nitrogen over a wide range of temperatures and pressures. The expressions used in calculating these properties have been made as simple in form as possible. For example, the thermodynamic properties can be approximated to within a few percent of the more exact solution when only the predominant energy levels of the lower lying states for each molecular species are retained. The calculation of transport properties can also be simplified by the use of empirical criteria for deriving collision cross sections. As an indication that the approximations introduced are reasonable, the final portion of this paper will utilize the predicted thermodynamic and transport properties and shock-wave relations to show that the experimental and theoretically predicted interface temperature rises and integrals of thermal conductivity compare favorably with one another.

SYMBOLS

a	speed of sound (zero frequency), also thermal diffusivity
a_i, b_i	stoichiometric coefficients for components A_i and B_i
A_i, B_i	components of a chemical reaction
C	Sutherland's constant
c_i	specific heat per mol at constant density for component i
c_p	specific heat per mol at constant pressure
c_v	specific heat per mol at constant density
D	dissociation energy per molecule
e	base of natural logarithms, also electron charge
e^-	electron
E	energy per mol, also electric field strength
E_o	energy per mol at zero absolute temperature
g_i	degeneracy of the ith state
h	Planck's constant
H	enthalpy per mol
I	molecular moment of inertia, also ionization energy per molecule
k	Boltzmann constant, also thermal conductivity
k_o	reference coefficient of thermal conductivity
k_n	coefficient of thermal conductivity due to molecular collisions
k_r	coefficient of thermal conductivity due to chemical reaction
K_c	chemical equilibrium constant for concentration units

K_p	chemical equilibrium constant for pressure units
m	mass of a particle
M_i	molecular weight per mol of component i
$\overline{M}$	mean molecular weight per mol of a gas mixture
M_o	molecular weight per mol for undissociated molecules
M_s	shock-wave Mach number
n	vibrational quantum number; electronic quantum number; and concentration in moles per unit volume
N	nitrogen atom, also atoms in general
N^+	singly ionized nitrogen
N^{++}	doubly ionized nitrogen
N_2	nitrogen molecule
O^{++}	doubly ionized oxygen
p	pressure
p_o	reference pressure, 1 atmosphere
$p(A_i)$, $p(B_i)$,...	partial pressure of components A_i, B_i, . . .
q	ionic charge
Q	total partition function
Q_c	total partition function for a standard state of unit concentration, $\frac{p}{RT} Q$
Q_p	total partition function for a standard state of unit pressure, pQ
$Q_p(A_i)$, $Q_p(B_i)$,...	total partition functions for components A_i, B_i, . . .
r	distance between atoms
r_e	distance between atoms in a molecule where the potential energy is a minimum

R	universal gas constant, energy per mol, deg
S	entropy per mol
S_i	entropy per mol of component i at 1 atmosphere pressure
S_o	collision cross section for undissociated air molecules
S_{ij} or $S(i\text{-}j)$	collision cross section for particle i with particle j
t	time
T	absolute temperature
u_i	mean molecular velocity for molecule type i
u_o	mean molecular velocity for undissociated air molecules
U	potential energy between gas particles
V	volume
x	mol fraction, or distance
x_i	mol fraction of component i
$x(A_i)$, ...	mol fraction of component A_i, . . .
Z	compressibility, $\dfrac{pM_o}{\rho RT}$ or $\dfrac{M_o}{\overline{M}}$
α	molecular symmetry number (equal 2 for homonuclear diatomic molecules), also polarizability
β	Morse function constant (eq. (36))
γ	ratio of specific heats, $\dfrac{c_p}{c_v}$
ϵ	fraction of molecules which are dissociated or of atoms which are ionized
ϵ_i	energy of the ith state
η	coefficient of viscosity
η_o	reference coefficient of viscosity

λ_i mean free path for molecule type i

λ_0 reference mean free path

ν vibrational frequency

ρ density

ρ_0 reference density

σ collision diameter

φ $\int_0^T k\,dT$, integral of thermal conductivity

φ^* $\int_0^T k^*dT$, integral of thermal conductivity for ideal gas

Subscripts

d dissociation reaction

i, j molecules type i and j

p constant pressure processes

s constant entropy processes

t,r,v,e contribution of translational, rotational, vibrational,
and electronic energy modes, respectively

I single ionization reaction

II double ionization reaction

ρ constant density processes

∞ initial conditions in the gas medium, identified with
conditions following the reflection of the initial shock
wave

APPROXIMATE THERMODYNAMIC PROPERTIES

Physical Model

The real-gas model which is assumed throughout the present paper
will be described. A convenient starting point is the ideal-gas model,

which is defined as one whose molecules are capable only of translational
and rotational degrees of freedom, are chemically inactive, and obey the
perfect gas law

$$pV = nRT \qquad (1)$$

where n, the number of mols, remains constant. The real-gas model,
which will be used, is capable of vibrational and electronic excitation
in addition to the translational and rotational modes, and is capable
of the following reactions: dissociation, single ionization, and double
ionization. The form of the perfect gas law is still retained; however,
the quantity n is no longer a constant, but is now a function of the
additional particles produced by the reactions. Equation (1) implies
that the molecule spends the greatest part of its time in field free
space, but allows short-range interactions (i.e., collisions) to occur.
The validity of this assumption has been verified theoretically by Duclos
(ref. 15) even for the extreme case of a completely ionized gas.

                          General Procedure

     The calculation of the thermodynamic properties of equilibrium
nitrogen is performed in three steps. The first step is to calculate
the thermodynamic functions for each of the particles (i.e., N_2, N, N^+,
N^{++}, and e^-) which participate in the various reactions. The term
"thermodynamic function" is used to describe variables, such as energy,
entropy, and specific heats, for a given particle, while the term
"thermodynamic property" is the corresponding term for an equilibrium
mixture of the participating particles. The basic parameter for this
calculation is the partition function, whose value is based on spectro-
scopic data. The second step is to determine the proportionate number
of each particle present at a given temperature and pressure. These
proportions are expressed in terms of the equilibrium mol fractions.
The third step is the calculation of the thermodynamic properties of
the mixture. This consists of a summation of the separate thermodynamic
functions which have been weighted by the equilibrium mol fractions.

                          Partition Function

     The partition function of a given particle is the sum of the
thermodynamic probabilities of the energy states available to the particle
(ref. 16). Its utility lies in the fact that all thermodynamic functions
can be expressed in terms of the partition function. Consequently, the
first step in determining the thermodynamic properties of an equilibrium
mixture of gases is to calculate the partition function for the component
particles. This function for a given mode of energy is defined as

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$$Q = \sum_{i=1}^{\infty} g_i \, \exp(-\epsilon_i/kT) \tag{2}$$

where ϵ_i is the ith quantum energy level, and g_i is the degeneracy or the total number of states which have different internal configurations but have the same energy level. The different modes of energy may be due to translation, rotation, or vibration of the particle, or to the motion of the electrons within the particle. The usual assumption is made that no coupling exists between the different modes of energy. The total energy of the particle can then be expressed as the sum of independent terms

$$\epsilon = \epsilon_t + \epsilon_r + \epsilon_v + \epsilon_e \tag{3}$$

As a result, the partition function can be expressed as the product of the component partition functions

$$Q = Q_t Q_r Q_v Q_e \tag{4}$$

The factors on the right side of equations (3) and (4) are, respectively, the energies and partition functions associated with translational, rotational, vibrational, and electronic energy levels of the gas particle. Each factor is determined independently by an equation of the same form as equation (2). The quantum mechanical expressions for the various components of equation (4) are available in reference 4. Only the ground state was used for the calculation of the electronic partition function for molecular nitrogen because of the extremely low probability of the molecule existing in the next excited state. The electronic partition functions for atomic and ionic nitrogen are expressed in closed form by restricting the summation to a finite number of terms. The cutoff terms are arbitrarily taken where the outer electron energy initially reaches the excited state corresponding to the fifth principle quantum number. Configurations of higher electronic energy levels have been grouped together to facilitate calculations, and the average energy level is used for that group of individual degeneracies. In the following table the partition function calculated by means of the exact energy levels is compared with those calculated by means of the approximate averaged energy levels for several arbitrary cutoff terms. The case of doubly ionized nitrogen at 30,000° K is used as an example. The table also shows the rate of convergence as the number of terms is increased.

Cutoff term	Exact Q	[1]Approximate $\bar{Q}$
1 (ground state)	2.000000	2.000000
2	5.966672	5.966672
5	6.736404	6.736419
10	6.822575	6.824390
32	6.823920	6.825352
54	6.823944	6.825377

Table I presents the atomic and molecular constants used in calculating the partition functions. The molecular constants for rotation, vibration, dissociation energy, and electronic energy levels were taken from Herzberg (ref. 17). The 9.76 electron-volt value for nitrogen dissociation is used, and it is assumed that the rotational and vibrational constants for all excited electronic states are the same as for the ground state. The atomic energy levels, as derived from spectroscopic analyses, are taken from Moore (ref. 18).

The functions to be used directly in the calculations that follow are the logarithms of the partition functions. The functions for the various nitrogen particles are

$$ \ln Q(N_2) = \frac{7}{2} \ln T - 0.42155 - \ln\left[1.00 - \exp\left(-\frac{3383.8}{T}\right)\right] - \ln p \qquad (5a) $$

$$ \ln Q(N) = \frac{5}{2} \ln T + 0.29359 + \ln\left[\sum_i g_i \exp(-\epsilon_i/kT)\right] - \ln p \qquad (5b) $$

$$ \ln Q(N^+) = \frac{5}{2} \ln T + 0.29359 + \ln\left[\sum_j g_j \exp(-\epsilon_j/kT)\right] - \ln p \qquad (5c) $$

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[1]The approximate partition function for this case is grouped according to the following scheme:

$$ \bar{Q}(N^{++}) = Q_1 + Q_2 + \bar{Q}_{3-5} + \bar{Q}_{6-7} + Q_8 + \bar{Q}_{9-10} + \bar{Q}_{11-18} + \bar{Q}_{19-32} $$

$$ + \bar{Q}_{33-42} + \bar{Q}_{43-54} $$

where $\bar{Q}_{n-m}$ represents

$$ \sum_{i=n}^{m} g_i \exp[\epsilon(\text{arithmetically averaged from } n \text{ to } m)/kT] $$

$$\ln Q(N^{++}) = \frac{5}{2} \ln T + 0.29359 + \ln\left[\sum_k g_k \exp(-\epsilon_k/kT)\right] - \ln p \qquad (5d)$$

$$\ln Q(e^-) = \frac{5}{2} \ln T - 14.2341 - \ln p$$

where T is the temperature in degrees Kelvin and p is expressed in atmospheres. The values for $g_{i,j,k}$ and $\epsilon_{i,j,k}$ are tabulated in table I.

Thermodynamic Functions for the Various Forms of Nitrogen

According to statistical mechanics, the energy and enthalpy per mol of a substance of homogenous chemical composition are given by the following relations:

$$\frac{E - E_0}{RT} = T\left(\frac{\partial \ln Q}{\partial T}\right)_\rho = T\frac{d \ln Q_c}{dT} \qquad (6)$$

$$\frac{H - E_0}{RT} = T\left(\frac{\partial \ln Q}{\partial T}\right)_p = T\frac{d \ln Q_p}{dT} \qquad (7)$$

The quantities Q_c and Q_p are the partition functions for the standard states of unit concentration and of unit pressure, respectively. These are related to the total partition function by

$$Q_c = \frac{p}{RT} Q \qquad (8)$$

$$Q_p = pQ \qquad (9)$$

and they are functions only of temperature so that it is their total derivatives which are related to the energy and enthalpy as given in equations (6) and (7). The quantity E_0 is a constant representing the total reaction energy of the particle. The choice of this level is arbitrary, but by convention, E_0 is taken as zero for the nitrogen molecule. Then E_0 for the neutral atom is just one-half the energy of dissociation per mol of diatomic molecules, E_0 for the singly ionized atoms is the sum of the preceding energy for the neutral atom and the first ionization potential, and so on.

The remaining thermodynamic functions, the specific heats at constant density and at constant pressure, and the entropy, are expressed in terms of the partition functions as follows:

$$c_V = \left(\frac{\partial E}{\partial T}\right)_\rho = 2RT \left(\frac{\partial \ln Q}{\partial T}\right)_\rho + RT^2 \left(\frac{\partial^2 \ln Q}{\partial T^2}\right)_\rho \qquad (10)$$

$$c_p = \left(\frac{\partial H}{\partial T}\right)_p = 2RT \left(\frac{\partial \ln Q}{\partial T}\right)_p + RT^2 \left(\frac{\partial^2 \ln Q}{\partial T^2}\right)_p \qquad (11)$$

$$\frac{S}{R} = \ln Q + T \left(\frac{\partial \ln Q}{\partial T}\right)_p \qquad (12)$$

Equations (6), (7), (10), (11), and (12) expressed in terms of the degeneracies and quantum energy levels can be found in reference 4.

Equilibrium Constants

The equilibrium constant for a given reaction is the basis for the determination of the equilibrium mol fractions of the components of nitrogen. The reactions considered here are the dissociation of molecular nitrogen, and the single and double ionization of atomic nitrogen. A simplifying assumption is made that each reaction occurs independently (i.e., one reaction is completed before another reaction is initiated). A later examination of the resulting thermodynamic properties will determine the validity of this assumption. The general expression for a chemical reaction is given as

$$\sum_i a_i A_i \rightleftarrows \sum_i b_i B_i \qquad (13)$$

where the reactants are A_i and the products are B_i. The pressure equilibrium constant can then be related to the partition function (ref. 19) by

$$\ln K_p = -\frac{\Delta E_o}{RT} + \sum_i b_i \ln Q_p(B_i) - \sum_i a_i \ln Q_p(A_i) \qquad (14)$$

where

$$\Delta E_O = \sum_i b_i E_O(B_i) - \sum_i a_i E_O(A_i) \tag{15}$$

is the zero point energy of the products less the zero point energy of the reactants, both referred to their standard states. The pressure equilibrium constants for the independent reactions, expressed in terms of the partition functions, are

$$\ln K_p(N_2 \rightarrow 2N) = -\frac{113,228}{T} + 2 \ln Q_p(N) - \ln Q_p(N_2) \tag{16a}$$

$$\ln K_p(N \rightarrow N^+ + e^-) = -\frac{168,750}{T} + \ln Q_p(N^+) + \ln Q_p(e^-) - \ln Q_p(N) \tag{16b}$$

$$\ln K_p(N^+ \rightarrow N^{++} + e^-) = -\frac{343,593}{T} + \ln Q_p(N^{++}) + \ln Q_p(e^-) - \ln Q_p(N^+) \tag{16c}$$

The concentration equilibrium constant, K_c, can be related to the pressure equilibrium constant, K_p, by substitution of equations (8) and (9) into the corresponding forms of equation (14). The resulting relation has the form

$$K_c = K_p(RT)^{\sum_i a_i - \sum_i b_i} \tag{17}$$

The logarithmic derivatives of the equilibrium constants will also be required later. From equations (6), (7), and (14) these become

$$T \frac{d \ln K_c}{dT} = \frac{\Delta E_O}{RT} + \sum_i b_i \left(\frac{E - E_O}{RT}\right)_{B_i} - \sum_i a_i \left(\frac{E - E_O}{RT}\right)_{A_i} \tag{18}$$

$$T \frac{d \ln K_p}{dT} = T \frac{d \ln K_c}{dT} + \sum_i b_i - \sum_i a_i \tag{19}$$

The equilibrium constants and their logarithmic derivatives now will be used in calculating the component mol fractions and their derivatives.

Equilibrium Mol Fractions and Their Derivatives

A comparison of the dissociation energy and the first and second ionization potentials indicates that the three chemical reactions will be relatively independent of one another. The assumption of independence permits the separate solution of the equilibrium mol fractions of the participating particles in each of the three independent reactions. The expressions for the equilibrium mol fractions and their derivatives are presented in table II. The procedure for calculating these parameters will be outlined in the next paragraph for the case of nitrogen dissociation and is exactly the same for the other two chemical reactions.

In the previous section it was shown that the equilibrium constant and its logarithmic derivative, for each reaction, can be determined from the known values of the partition functions for each of the participating particles. The equilibrium mol fraction can then be related to the pressure equilibrium constant by the following relation

$$K_p = \frac{\Pi[p(B_i)]^{b_i}}{\Pi[p(A_i)]^{a_i}} \tag{20}$$

where a_i and b_i are the stoichiometric coefficients from the general expression for a chemical reaction (eq. (13)), and $p(A_i)$ and $p(B_i)$ are the partial pressures of the reactants and products, respectively. The partial pressures, in turn, are just the product of the equilibrium mol fraction and the total pressure of the equilibrium mixture.

$$p(N_2) = x(N_2)p = \left(\frac{1 - \epsilon_d}{1 + \epsilon_d}\right) p \tag{21a}$$

$$p(N) = x(N)p = \left(\frac{2\epsilon_d}{1 + \epsilon_d}\right) p \tag{21b}$$

where ϵ_d is defined as the fraction of the initial number of mols which have become dissociated. Substitution of equations (21a) and (21b) into equation (20) results in

$$K_p(N_2 \to 2N) = \frac{p^2(N)}{p(N_2)} = \left(\frac{4\epsilon_d^2}{1 - \epsilon_d^2}\right) p \tag{22}$$

Then the resulting quadratic equation is solved for ϵ_d

$$\epsilon_d = \left(\frac{K_p}{4p + K_p}\right)^{1/2} \tag{23}$$

It is more convenient to express the equilibrium mol fractions in terms of ϵ_d, as this will simplify the expressions for the equation of state for the mixture, and the derivatives of the equilibrium mol fractions.

Since it is assumed that each component behaves like an ideal gas with respect to the equation of state, the equation for the gas mixture also takes the same form

$$\frac{p}{\rho} = \frac{ZRT}{M_O} \tag{24}$$

This equation is equivalent to equation (1). The quantity Z is called the compressibility and it represents the total number of mols per initial mol of undissociated nitrogen, or equivalently, the ratio of the initial molecular weight of undissociated nitrogen to the mean molecular weight, $M_O/\overline{M}$. For this case, Z_d is equal to $1 + \epsilon_d$. The differentiation of equation (23) yields the expression for $(\partial \epsilon_d/\partial T)_p$ in terms of the known quantity, $d \ln K_p/dT$ (eq. (19)), and the differentiation of equations (21a) and (21b) yields the derivative of the product of the compressibility and mol fraction, $(\partial Z_d x_i/\partial T)_p$ in terms of $(\partial \epsilon_d/\partial T)_p$. These expressions are shown in table II. The corresponding equations in terms of the concentration equilibrium constant, K_c, can be derived from the conversion relation

$$K_c = K_p \frac{\rho Z_d}{pM_O} = K_p \left(\frac{1 + \epsilon_d}{pM_O}\right) \rho \tag{25}$$

which is obtained by combining the equation of state (eq. (24)) with equation (17). The conversion relation is then substituted into equation (22) to obtain K_c as a function of ϵ_d. The derivatives of the equilibrium mol fractions at constant density are obtained by using K_c in place of K_p and proceeding in exactly the same manner as shown for the constant pressure case. These constant density expressions are also shown in table II.

At this point, thermodynamic functions determined separately for each of the various forms of nitrogen can be combined with the equilibrium mol fractions and their corresponding derivatives to calculate the thermodynamic properties of an equilibrium mixture of the various forms of nitrogen for each of the three reactions. The properties which will be calculated are the energy, entropy, specific heats, and the speed-of-sound parameter.

Thermodynamic Properties of Equilibrium Nitrogen

The thermodynamic properties are given by the sum of the separate thermodynamic functions which have been weighted by the corresponding equilibrium mol fractions. Generally in engineering calculations the energy per fixed mass of gas is needed rather than the energy per mol. This quantity can be obtained by multiplying E/RT, the energy mol, by Z, the total number of mols per initial mol of undissociated nitrogen. The result is the energy per mol of initially undissociated nitrogen (i.e., a fixed mass of 28.015 grams), and is given as

$$\frac{ZE}{RT} = Z \sum_i x_i \frac{E_i}{RT} \qquad (26)$$

where the summation i extends to all reactants and products of a given reaction, and where E_i is the energy per mol for component i. The dimensionless enthalpy per initial mol of nitrogen becomes

$$\frac{ZH}{RT} = \frac{ZE}{RT} + Z \qquad (27)$$

The compressibility, Z, dimensionless energy, ZE/RT, and dimensionless enthalpy, ZH/RT, which have been calculated from the preceding equations, are listed in tables III(a), III(b), and III(c). The compressibility and energy are shown as functions of temperature in figures 1 and 2. The entropy per initial mol of nitrogen is obtained from the separate entropies of the various species by the summation

$$\frac{ZS}{R} = Z \left(\sum_i x_i \frac{S_i}{R} - \sum_i x_i \ln x_i - \ln \frac{p}{p_o} \right) \qquad (28)$$

where p_o is the reference pressure for the standard state, in this case 1 atmosphere, and S_i/R is the entropy of component i at 1 atmosphere. The entropy values are listed in table III(d), and also are shown in figure 3.

The specific heats are strictly defined as the rate of change of the total internal energy (for c_v) or total enthalpy (for c_p) with the change in temperature for a fixed mass of gas. Since the total internal energy (or enthalpy) is the sum of the products of three temperature-dependent factors, E_i, x_i, and Z, the $E_i(\partial Z x_i/\partial T)$ terms must be included as well as the $Z x_i(\partial E_i/\partial T)$ terms. The specific heat at constant density per initial mol of undissociated nitrogen is given by

$$\frac{Zc_v}{R} = Z \sum_i x_i \frac{c_i}{R} + T \sum_i \frac{E_i}{RT}\left(\frac{\partial Zx_i}{\partial T}\right)_\rho \qquad (29)$$

where c_i is the derivative of energy for component i, that is dE_i/dT. The corresponding equation for the specific heat at constant pressure is

$$\frac{Zc_p}{R} = Z \sum_i x_i \left(\frac{c_i}{R} + 1\right) + T \sum_i \left(\frac{E_i}{RT} + 1\right)\left(\frac{\partial Zx_i}{\partial T}\right)_p \qquad (30)$$

The specific heats calculated from equations (29) and (30) are listed in tables III(e) and III(f), and are presented in figures 4 and 5.

The speed of sound in nitrogen can be calculated from the specific heat values determined above. The dimensionless speed-of-sound parameter, $a^2\rho/p$, was derived in reference 4, in terms of variables already calculated

$$\frac{a^2\rho}{p} = \gamma\,\frac{1 + (T/Z)(\partial Z/\partial T)_\rho}{1 + (T/Z)(\partial Z/\partial T)_p} \qquad (31)$$

This dimensionless speed-of-sound parameter is listed in table III(g), and is shown in figure 6 as a function of temperature.

Discussion of Results

The criterion for the reactions to proceed independently of one another, as previously assumed, is that the derivatives, $(\partial Z/\partial T)_p$, for the successive reactions vanish in the transition region. Figure 7 shows the compressibility and dimensionless energy which were computed separately for each of the three chemical reactions. It is seen that the continuity requirement is approximately satisfied except at the highest pressures. This comparison justifies our original assumption of reaction independency.

The final tabulated and plotted curves of the thermodynamic properties in table III and figures 1 through 6 are presented with the discontinuity faired out by use of the compressibilities for each of the three reactions (see table II) as weighting functions. For example, the corrected compressibility and dimensionless energy are, respectively, expressed as

$$Z = 1 + \epsilon_d + 2\epsilon_I + 2\epsilon_{II} \qquad (32)$$

$$\frac{ZE}{RT} = \left(\frac{ZE}{RT}\right)_d + \frac{Z_I - 2}{Z_I - Z_d}\left[\left(\frac{ZE}{RT}\right)_I - \left(\frac{ZE}{RT}\right)_d\right] + \frac{Z_{II} - 4}{Z_{II} - Z_I}\left[\left(\frac{ZE}{RT}\right)_{II} - \left(\frac{ZE}{RT}\right)_I\right] \tag{33}$$

where the subscripts d, I, and II refer, respectively, to the dissociation, single ionization, and double ionization reactions.

For the purpose of discussion, it is convenient to divide both the thermodynamic properties and the transport properties (to be discussed in a subsequent section) into two categories. The properties of the first group are characterized by a dependency only on ϵ, the fraction of initial particles which have become either ionized or dissociated. The quantity ϵ is a measure of the equilibrium composition of the gas. The properties of the second group are dependent on the partial derivative $\partial\epsilon/\partial T$, as well as on ϵ itself. This partial derivative is a measure of the change in the equilibrium state with increase in temperature, since it can be seen in table II that $\partial\epsilon/\partial T$ is directly proportional to $\partial K_p/\partial T$ or $\partial K_c/\partial T$.

The ϵ dependent thermodynamic properties include the compressibility, Z, the energy, ZE/R, the enthalpy, ZH/R, and the entropy, ZS/R. These parameters increase gradually with temperature as the first reaction proceeds then level off as the reaction approaches completion. This is followed by similar variations to higher levels for each of the succeeding reactions (see fig. 3). The thermodynamic properties dependent on $\partial\epsilon/\partial T$ include the specific heats at constant density and pressure, Zc_v/R and Zc_p/R, and the speed-of-sound parameter, $a^2\rho/p$. The relative effects of ϵ and $\partial\epsilon/\partial T$ on the thermodynamic properties in this second group can be seen by separating the expressions for these properties into the ϵ components and the $\partial\epsilon/\partial T$ components. For example, the expression for Zc_v/R (eq. (29)) can be written explicitly in terms of ϵ and $(\partial\epsilon/\partial T)_\rho$ for the double ionization reaction

$$\frac{Zc_v}{R} = \left[(2 - 2\epsilon_{II})\frac{c_v}{R}(N^+) + 2\epsilon_{II}\frac{c_v}{R}(N^{++}) + (2 + 2\epsilon_{II})\frac{c_v}{R}(e^-)\right]$$

$$+ 2T\left(\frac{\partial\epsilon_{II}}{\partial T}\right)\left[-\frac{E}{RT}(N^+) + \frac{E}{RT}(N^{++}) + \frac{E}{RT}(e^-)\right] \tag{34}$$

Similar expressions exist for the case of dissociation and single ionization. The resulting ϵ and $\partial\epsilon/\partial T$ components of Zc_v/R for the three reactions are compared in figure 8. It can be seen that the ϵ component is negligible in all three cases, and that it is the $\partial\epsilon/\partial T$ component which determines the temperature variation of Zc_v/R. The dominance of the $\partial\epsilon/\partial T$ component can be attributed to the large value of the reaction energy, E_0, contained in the E/RT factor, as compared to the magnitude of the c_v/R factor in the ϵ component. The properties dependent on $\partial\epsilon/\partial T$ are characterized by a distinct peak for each of the three reactions as the corresponding $\partial K_p/\partial T$ approaches a maximum. The dimensionless specific heat at constant pressure, Zc_p/R, has the same type of

temperature variation. The speed-of-sound parameter, $a^2\rho/p$, does not exhibit a similar regularity since it is a function of two $\partial\epsilon/\partial T$ parameters (eq. (31)) which peak at slightly different temperatures.

The possibility is great that the behavior of nitrogen is representative of the behavior of air, since nitrogen is the main constituent of air. Comparison of the calculated thermodynamic properties of air from reference 4 with those of nitrogen in figure 9 shows that this is certainly the case from the point where oxygen is completely dissociated (Z = 1.2) up to the point where single ionization of oxygen and nitrogen is completed (Z = 4.0). No comprehensive set of thermodynamic and transport data for air has been presented at higher temperatures where double ionization becomes important, although Gilmore has presented exact thermodynamic calculations for equilibrium air at selected temperatures of 18,000° K and 24,000° K (ref. 1). In this light, a simplified gas model is assumed for calculating the thermodynamic properties of equilibrium air whose components, nitrogen and oxygen, are undergoing double ionization. These properties will then be compared with the previously calculated thermodynamic properties of pure nitrogen for a few conditions to give an indication of the changes introduced by the presence of the oxygen components. The few exact points calculated by Gilmore will also be compared with the nitrogen data of this paper. The same type of comparisons will be made for transport properties in a subsequent section.

A gas model is assumed in which the nitrogen ions, N^+, and oxygen ions, O^+, undergo a successive ionization to N^{++} and O^{++} simultaneously but independently. The term "independently," in this case, describes a reaction which has no effect on the equilibrium constant for the other simultaneous reaction, and vice versa. In addition, it is assumed as a first approximation that the pressures of the nitrogen mixture and the oxygen mixture are each equal to the total pressure. These assumptions permit the direct use of the previously calculated thermodynamic properties of nitrogen, and also permit the use of the same procedures for calculating the thermodynamic properties of oxygen. The second ionization potential and electronic energy levels for doubly ionized oxygen are taken from reference 18. The thermodynamic properties for this simplified model of air are then obtained by weighting the nitrogen and oxygen values in the ratio of 4 to 1 to account for their proportions in air, and adding these weighted values. The only effect of any consequence which cannot be accounted for in this approximation is the influence of the products N^{++} and e^-, resulting from the double ionization of nitrogen, on the equilibrium balance for the double ionization of oxygen. The products, O^{++} and e^-, resulting from the double ionization of oxygen should not have any noticeable effect on the double ionization of nitrogen because of the higher second ionization potential for oxygen and the lower proportion of oxygen particles.

The computational procedures previously described for nitrogen were also used for the oxygen component of the simplified air mixture. The

dissimilarities between the nitrogen and oxygen values of the electronic partition function and the second ionization potential are shown in the following table:

	N^{++}	O^{++}
	Second ionization potential	
	29.605 e.v.	35.146 e.v.
Temperature $^\circ K$	Electronic partition function	
20,000	6.152	10.143
25,000	6.437	10.706
30,000	6.875	11.260

These dissimilarities result in large differences in ϵ_{II} and in $\partial \epsilon_{II}/\partial T$ (fig. 10). It is these differences which are mainly responsible for any deviation between the properties of nitrogen and air.

The thermodynamic properties of nitrogen are compared in figure 9 with those for the simplified model of air, in the region where double ionization of oxygen and nitrogen particles occurs. It can be seen that the ϵ dependent thermodynamic properties (Z, ZE/RT, ZH/RT, and ZS/R) for air and nitrogen have the same temperature variation and approach each other in magnitude. The largest difference in magnitude is approximately 7-1/2 percent and in most cases is much less than this. The $\partial \epsilon/\partial T$ dependent thermodynamic properties (Zc_V/R, Zc_p/R, and $a^2 \rho/p$) were shown previously to consist of a series of sharp peaks due to the predominance of the $\partial \epsilon/\partial T$ term. The location and magnitude of these peaks are of primary concern. The magnitudes of these peaks for air and nitrogen are within 2 to 12 percent of one another, depending on the pressure. The temperature at which these peaks occur is predicted with a difference of only 2 percent. The prediction of points off the peak shows marked differences due to the abrupt changes with temperature (fig. 9).

The approximated thermodynamic properties of air were easily calculated in this paper because reaction interactions were neglected. These complex interactions were accounted for in the exact solution of Gilmore (ref. 1). In the region where double ionization of nitrogen and oxygen becomes important, thermodynamic properties were calculated by Gilmore only at temperatures of 18,000° K and 24,000° K. However, these points can be used to determine the degree of approximation introduced by the assumption of the simplified air model. The approximated ϵ_{II} for the nitrogen and oxygen components are compared in figure 11 with those from reference 1. The values for the nitrogen components compare favorably, as expected, whereas the comparison indicates that the assumptions

have resulted in a decrease in the amount of doubly ionized oxygen at a
given temperature and pressure. The exact values of ϵ_{II} for oxygen lie
between the ϵ_{II} values for the oxygen component of the simplified model
of air and the calculated nitrogen values. It is expected that the same
trends would hold for $\partial \epsilon_{II}/\partial T$ (see table II). Therefore, the thermo-
dynamic properties for the simplified model of air with its smaller values
of ϵ_{II} and $\partial \epsilon_{II}/\partial T$ for the oxygen component are a fair estimate, and a
more realistic model would result in better correspondence between the
thermodynamic properties of nitrogen and air. This trend is also shown
in figure 9 where the exact air values for Z, ZE/RT, and ZS/R from
reference 1 are compared with those for nitrogen and for the simplified
model of air.

APPROXIMATE TRANSPORT PROPERTIES

Accurate values of the thermodynamic properties of gases may be
calculated by use of quantum statistical theory because of the availa-
bility of spectroscopically determined atomic and molecular energy
levels (refs. 17 and 18). Expressions for the transport properties due
to binary collisions have also been derived by Hirschfelder in refer-
ence 20. However, the determination of the fundamental variables, the
collision integrals, has not proven amenable to either experimental or
theoretical solution for binary collisions of most gases. As a result
approximate theories must be used, in contrast to the more exact theories
for the thermodynamic properties.

The development of the elementary theory of transport phenomena from
collision considerations can be found in references 13 and 21. The
approach taken in this paper is to express the mean free path in terms of
the effective collision cross section, S. The quantity S is then used
as the fundamental quantity for calculating the coefficient of viscosity
and the coefficient of thermal conduction due to the combined effects of
collision and diffusion. The expressions for the effective cross sections
for collisions between the various particles will be listed in the follow-
ing paragraphs. A discussion of the origin and qualitative aspects of
these collision cross sections is available in reference 4.

Collisions between nitrogen molecules can be approximated by a hard
sphere model with a superimposed repulsive force which asymtotically goes
to zero at higher temperatures. The effective collision cross section
for this model, S_0, is expressed by the Sutherland formula

$$S_0 = S_\infty \left(1 + \frac{C}{T} \right) \tag{35}$$

For nitrogen C is the empirically determined constant equal to 112.0° K,
and S_∞ is the molecular cross section of the hard sphere model and is
equal to 3.14×10^{-15} cm^2. The quantity S_0 will also be used to express

all collision cross sections in dimensionless form, as the expressions for viscosity and thermal conductivity require the cross sections in the ratio form S_{ij}/S_o, where S_{ij} is the effective cross section for collisions between type i and j particles.

The subsequent collision cross sections are determined by the assumption that the collision radius is the interparticle distance where the interparticle potential is equal to an empirically determined value. For the transfer of momentum and energy this value is taken equal to $-kT$, and for diffusion this value is equal to $-2kT$. The atom-atom potential may be approximated by the Morse function (ref. 10). The resulting effective diameter for collision between nitrogen atoms is

$$\frac{\sigma}{r_e} = 1 - \frac{1}{\beta} \ln\left(1 - \sqrt{1 - \frac{kT}{D}}\,\right) \tag{36a}$$

for momentum and energy transfer, and

$$\frac{\sigma}{r_e} = 1 - \frac{1}{\beta} \ln\left(1 - \sqrt{1 - \frac{2kT}{D}}\,\right) \tag{36b}$$

for diffusion; where D is the dissociation energy; r_e is the interatomic distance at which U_o, the lowest lying potential, is a minimum; and β is a constant related to the vibrational frequency of the stable molecule. These constants were taken from Herzberg (ref. 17) and are listed in the following table:

Colliding particles	D/k, $^o K$	β	r_e, angstrom
N - N	113,230	2.943	1.094
N - N$^+$	101,250	2.940	1.116

The atom molecule collision diameter will be taken as the arithmetic average of the atom-atom and of the molecule-molecule collision diameters.

The remaining collision cross sections for the single and double ionization reactions are relatively simple to calculate. The coulomb type force exists during an encounter between two charged particles. As before, the collision diameter for momentum and energy transport is defined as the interparticle distance where the modified coulomb potential is equal to $-kT$. In view of the order of the approximations involved, these cross sections are also assumed for the case of diffusion. The expression for the collision diameter for two particles thus becomes

$$\sigma_{ij} = q_i q_j \frac{e^2}{kT} \ln \Lambda \tag{37}$$

The quantity $q_i q_j$ is the product of the ionic charges for the inter-acting charged particles. The second factor, $\ln \Lambda$, is a shielding correction which occurs in a plasma of finite density. The derivation of this correction is given in reference 22. For the case of single ionization the correction is

$$\ln \Lambda_I = \ln \left\{ 1.0231\times10^{-7} T^2 [x(e^-)p]^{-1/2} \right\} \tag{38}$$

For the case of double ionization the correction is

$$\ln \Lambda_{II} = \ln \left\{ 1.4468\times10^{-7}\, \frac{T^2}{\bar{q}_{II}}\, [x(e^-)p(\bar{q}_{II} + 1)]^{-1/2} \right\} \tag{39}$$

where

$$\bar{q}_{II} = \frac{x(N^+) + 2x(N^{++})}{x(N^+) + x(N^{++})} \tag{40}$$

At the densities considered here, the effects of this correction are not very large until the gas is almost completely ionized. The single ion-atom collision may be treated in the same manner as the atom-atom colli-sions, since the spectroscopic data for ionized molecules are available and can be used in setting up the Morse function between the ion and the neutral atom. The constants for this case are also listed in the preceding table.

Encounter of an electron with an atom will polarize the atom, resulting in a charge-dipole interaction. The potential resulting from the classical dipole interaction is assumed, and the resulting collision diameter for energy transport, momentum transport, and diffusion is then equal to

$$\sigma = \left(\frac{e^2 \alpha}{2kT} \right)^{1/4} \tag{41}$$

where α, the polarizability, is equal to 10.38×10^{-25} cm^3 for nitrogen (ref. 4).

Viscosity

The viscosity of nitrogen will be calculated from the simple summation formula for a mixture of hard spherical molecules similar to the one given by Kennard in reference 21

$$\eta = \frac{5\pi}{32} \sum_i \rho_i u_i \lambda_i \tag{42}$$

where

$$\lambda_i = \frac{1}{2n \sum_j x_j S_{ij} \left(1 + \frac{M_i}{M_j}\right)^{-1/2}} \tag{43}$$

and where n denotes the concentration in moles per unit volume. This expression for the mean free path was developed from the more rigorous form given in reference 20, and differs from the corresponding expression of reference 21 in two respects. First, the exponent of the mass term is $-1/2$ rather than $+1/2$, and second, a factor of 2 appears in the denominator. An explanation of these discrepancies can be found in reference 23.

In the subsequent calculation of viscosity, it will be convenient to use, as a reference value, the viscosity which nitrogen would have at the same temperature if the molecules did not dissociate or ionize

$$\eta_o = \frac{5\pi}{32} \rho_o u_o \lambda_o = 1.413 \times 10^{-5} \frac{\sqrt{T}}{1 + \frac{112}{T}} \frac{gm}{cm\text{-}sec} \tag{44}$$

Then the ratio of viscosity to the reference viscosity becomes

$$\frac{\eta}{\eta_o} = \sum_i \frac{\rho_i}{\rho_o} \frac{u_i}{u_o} \frac{\lambda_i}{\lambda_o} = \sum_i \left(\frac{M_i}{M_o} x_i\right) \left(\frac{M_o}{M_i}\right)^{1/2} \frac{\lambda_i}{\lambda_o} = \sum_i \left(\frac{M_i}{M_o}\right)^{1/2} x_i \frac{\lambda_i}{\lambda_o} \tag{45}$$

where the mean-free-path ratio is

$$\frac{\lambda_o}{\lambda_i} = \sum_j x_j \frac{S_{ij}}{S_o} \left(\frac{2}{1 + \frac{M_i}{M_j}}\right)^{1/2} \tag{46}$$

The coefficients of viscosity for high-temperature nitrogen have been calculated from equations (45) and (46) and the results are presented in table IV(a) and in figure 12. The terms in the summation of equation (46) will also be used in the evaluation of the coefficient of thermal conductivity.

Thermal Conductivity

The energy transfer, or thermal conductivity, through a high temperature, chemically reacting gas is treated in two independent parts. The first component is the energy transferred by molecular collisions, and this mode of energy transfer is the one responsible for the ordinary thermal conductivity of nonreacting gases. The second component is the energy transferred by diffusion of the molecular species and the reactions which occur as the gas tends to maintain itself in chemical equilibrium at each point. The component of thermal conductivity due to collisions, k_n, is given by the simple summation equation

$$k_n = \frac{5\pi}{32} \sum_i \rho_i u_i \frac{\lambda_i}{M_i} \left(\frac{5}{2} c_t + c_{int} \right)_i = \frac{5\pi}{32} \sum_i \lambda_i \rho_i u_i \left(\frac{c_i}{M_i} + \frac{9}{4} \frac{R}{M_i} \right) \qquad (47)$$

since c_i, the specific heat at constant density, is equal to the sum of c_t, the specific heat per mol due to translational energy $(3R/2)$, and c_{int}, the specific heat due to the internal energy.

It will be convenient to define a reference coefficient of thermal conductivity just as was done for the viscosity, that is, the value that nitrogen would have at the same temperature if the molecules did not dissociate or ionize

$$k_0 = \frac{5\pi}{32} \rho_0 u_0 \lambda_0 \left(\frac{19}{4} \frac{R}{M_0} \right) = \frac{19}{4} \frac{R}{M_0} \eta_0$$

$$= 1.992 \times 10^{-5} \frac{\sqrt{T}}{1 + \frac{112}{T}} \frac{Joule}{cm\text{-}sec\text{-}^0K} \qquad (48)$$

The ratio of the thermal conductivity coefficient to the reference coefficient becomes

$$\frac{k_n}{k_0} = \sum_i \left(\sqrt{\frac{M_i}{M_0}} x_i \frac{\lambda_i}{\lambda_0} \right) \frac{M_0}{M_i} \left(\frac{4}{19} \frac{c_i}{R} + \frac{9}{19} \right) \qquad (49)$$

The first factors in each term of the summation are just the terms already calculated for the viscosity.

The second mode of energy transfer, which takes place whenever the gas undergoes a chemical reaction, is due to the diffusion of the chemical species. These particles then react with one another, giving off or absorbing the heat of reaction and causing heat transfer which may be

considerably larger than the ordinary heat transfer due to molecular collisions. The expression for this component of thermal conductivity is taken from reference 24, and may be expressed as

$$\frac{k_r}{k_0} = \frac{\dfrac{12\sqrt{2}}{95}\left(T\,\dfrac{d\,\ln K_p}{dT}\right)^2}{\displaystyle\sum_i\sum_j\left[\dfrac{M_i M_j}{M_0(M_i + M_j)}\right]^{1/2}\dfrac{S'_{ij}a_i}{S_0 x_i}\,(a_i x_j - a_j x_i)} \tag{50}$$

where the prime denotes the cross section for diffusion, and a_i are the stoichiometric coefficients of components A_i in the chemical reaction written in the form

$$\sum_i a_i A_i = 0 \tag{51}$$

The double summations in the denominator of equation (50) take on the forms as follows:

Case I - Dissociation reaction

$$\sum_i\sum_j = \frac{1}{\sqrt{3}}\,\frac{S'(N_2 - N)}{S_0}\,\frac{[x(N) + 2x(N_2)]^2}{x(N)x(N_2)} \tag{52}$$

Case II - Single ionization reaction

$$\sum_i\sum_j = \left[\frac{1}{2}\,\frac{S'(N - N^+)}{S_0} + 4.425\times10^{-3}\,\frac{S'(N - e^-)}{S_0}\right]\frac{[x(N) + x(N^+)]^2}{x(N)x(N^+)} \tag{53}$$

Note that the $N^+ - e^-$ collision term disappears as the factor $\dfrac{[x(N^+) - x(e^-)]^2}{x(N^+)x(e^-)}$ is zero because of the equality of $x(N^+)$ and $x(e^-)$.

Case III - Double ionization reaction

$$\sum_i \sum_j = \frac{1}{2} \frac{S'(N^+ - N^{++})}{S_o} \frac{[x(N^+) + x(N^{++})]^2}{x(N^+)x(N^{++})}$$

$$+ 4.425 \times 10^{-3} \frac{S'(N^+ - e^-)}{S_o} \frac{[x(e^-) + x(N^+)]^2}{x(e^-)x(N^+)}$$

$$+ 4.425 \times 10^{-3} \frac{S'(N^{++} - e^-)}{S_o} \frac{[x(e^-) - x(N^{++})]^2}{x(e^-)x(N^{++})} \tag{54}$$

The total coefficient of thermal conductivity is the sum $k_n + k_r$. The values of this sum were calculated for nitrogen and the results are presented in figure 13 and table IV(b). The Prandtl numbers are calculated from the relation

$$Pr = \frac{c_p}{\overline{M}} \frac{\eta}{k} = \frac{4}{19} \frac{Zc_p}{R} \frac{\eta/\eta_o}{k/k_o} \tag{55}$$

and are listed in table IV(c) and are presented in figure 14.

Discussion of Results

The calculation of transport properties due to binary collisions required two approximations: (1) empirically determined collision cross sections in place of collision integrals, and (2) summations of momentum and energy exchange terms in place of the rigorously derived determinant form of reference 20. The degree of approximation brought about by use of an effective collision cross section is discussed in reference 4. The summation form is equivalent to setting the off-diagonal terms of the determinants equal to zero. An indication of the deviation due to this method can be obtained by a comparison of the transport properties of this paper with those computed by the similar method of reference 25, where the deviation from the determinant form is known. The expressions of reference 25 are similar to the summation form of this paper in that the off-diagonal terms are also neglected. The comparative data for the case of dissociation indicate that using the summation form in the present paper resulted in a maximum error of 4 percent for viscosity and 15 percent for thermal conductivity. The maximum error occurs at a point where nitrogen is about 50 percent dissociated. The errors vanish at the point where nitrogen is completely undissociated or completely dissociated. A qualitative inspection of the off-diagonal terms and the corresponding collision cross sections for the single and double ionization shows that the maximum errors are less than those quoted for the dissociation

reaction. The other calculated component of thermal conductivity, k_r, contains little error as this component (eq. (50)) is obtained directly from the rigorous solution.

The transport properties, like the thermodynamic properties, can be separated into ϵ dependent properties and $\partial\epsilon/\partial T$ dependent properties. The first group includes the coefficient of viscosity and the collision component of the coefficient of thermal conductivity k_n. The viscosity ratio shown in figure 12 is characterized by a slight rise with temperature as the amount of atomic nitrogen increases, followed by a sharp decrease in the region of ionization. These variations can be attributed to the fact that the viscosity ratio for each pair of colliding particles is inversely proportional to the size of the corresponding effective collision cross section (eqs. (46) and (47)). For dissociation, $S(N_2 - N)$ and $S(N - N)$ are slightly less than $S(N_2 - N_2)$, and for ionization, $S(N^+ - N^+)$ and $S(N^{++} - N^{++})$ are greater by several orders of magnitude than either $S(N - N)$ or $S(N - N^+)$.

A comparison of the two components of the coefficient of thermal conductivity, the ϵ dependent k_n and the $\partial\epsilon/\partial T$ dependent k_r (fig. 15), shows the relative effects of the two categories. It can be seen that the chemical reaction component, k_r/k_0, predominates for the dissociation and single ionization reaction, and is characterized by a steep rise with temperature as $\partial K_p/\partial T$ approaches a maximum, followed by a decrease as $\partial K_p/\partial T$ passes this maximum. The thermal conductivity ratio for the double ionization is unique in that the ϵ dependent term, k_n/k_0, is the predominate one. The factor which suppresses k_r/k_0 can be seen by inspection of the expression for the denominator of k_r/k_0 (eq. (54)). The magnitude of the denominator is determined by the first term on the right side since the other two terms prove to be negligible because of the small mass of the electron. Because of its coulombic nature, the collision cross section $S'(N^+ - N^{++})$ is larger by an order of magnitude than the corresponding ones for dissociation and single ionization $S'(N_2 - N)$ and $S'(N - N^+)$. This large value of $S'(N^+ - N^{++})$ thereby compensates for the peak value of $\partial \ln K_p/\partial T$ in equation (54).

The Prandtl number does not follow any of these variations since it contains the ratio of two $\partial\epsilon/\partial T$ dependent terms (eq. (55)). A discussion of the temperature variation of the Prandtl number is available in reference 4.

The transport properties for nitrogen are compared in figure 16 with those for air in the region of double ionization of oxygen and nitrogen atoms. The transport properties for the simplified model of air were calculated by the same procedure previously described for the thermodynamic properties. The trends shown for the comparative thermodynamic properties of air and nitrogen hold for the transport properties. The ratios of viscosity and thermal conductivity for air and nitrogen are predominantly ϵ dependent and, as a result, have approximately the same value over the range of double ionization. The Prandtl numbers are $\partial\epsilon/\partial T$ dependent and, as a result, are comparable only for peak values.

SHOCK-TUBE APPLICATIONS

The theoretical values of the integral of thermal conductivity for air were compared with the experimental values in references 11 and 12. Although nitrogen is the major constituent of air, the component of thermal conductivity due to nitrogen was completely masked by the oxygen component because of the much lower dissociation energy of oxygen. For this reason, it is necessary that an independent evaluation of the integral of thermal conductivity for pure nitrogen be made.

The first step in the shock-tube evaluation of transport properties is to determine the state variables, p, T, ρ, and h, behind the incident and reflected shock by use of the previously calculated thermodynamic properties of nitrogen. For a range of temperatures and pressures where the ideal gas behavior is no longer valid, the shock-tube relations cannot be given analytically in terms of initial conditions, but must be obtained by iteration. A general outline of the iteration procedure is presented in reference 26 and in the introduction to reference 3. The iterative solutions are presented in figures 17, 18, and 19 as functions of the shock-wave Mach number, M_S - the speed of the shock wave divided by the speed of sound in undisturbed nitrogen. The calculations were carried out to a maximum M_S of 34. The state variables are presented as the ratio of the calculated real-gas variable to that for the ideal gas (appendix A). This dimensionless form was chosen in order to maintain the same degree of accuracy on the graphs throughout the range of shock-wave Mach numbers. The solutions are shown for combinations of three initial temperatures, 293° K (fig. 17), 400° K (fig. 18), and 500° K (fig. 19), and six initial pressures varying from 1.0 to 10^{-5} atmospheres. Subscript 1 refers to the initial conditions and subscript 2 to the conditions following the normal shock. Subscript 3 refers to the conditions following the reflection of the normal shock from the closed end of the shock tube. The superscript * denotes the ideal-gas condition. The expressions for the ideal-gas variables behind incident and reflected shocks are given in appendix A for convenience. Note that the displacements of the curves are about proportional to the logarithm of the initial pressure p_1 so it is possible to interpolate between the curves with reasonable accuracy.

A similar set of calculations for air was presented in reference 10 for an initial temperature of 293° K. The calculations were carried out to a maximum shock-wave Mach number of 16 (approximately corresponding to T_3 = 15,000° K). The similarity of thermodynamic properties for air and nitrogen indicates that the nitrogen shock properties may be similar to those for air, beyond the range of the data in reference 10. An inspection of the terms in the basic shock equation used in the iterative calculation shows that the required thermodynamic properties are all ϵ dependent. The thermodynamic properties for air and nitrogen in this category were shown to be within at least 4 percent of one another for the range of temperatures and pressures considered. As a result, the

shock-wave relations for nitrogen can be substituted for those of air with the same order of deviation for incident shock strengths where the compressibility factor of the air behind the incident shock is greater than 1.5. This criterion is shown as a dotted line in figures 17, 18, and 19.

The experimental and theoretical thermal conductivity of nitrogen can be compared once the computed state variables behind incident and reflected shocks are available. The highest temperatures attained in the shock tube are generated by the reflection of the shock wave off the end of the tube. The thermal situation can be represented by convective and conductive heat transfer between a semi-infinite solid with a uniform initial temperature and a semi-infinite, shock-heated, high-temperature gas with a uniform initial temperature. The two media are separated by an interface whose temperature remains constant with time after the initial contact. Two similar analyses of this particular configuration provide conductivity-dependent parameters which can be used in the experimental and theoretical comparison. The first analysis, developed by Thomson in reference 27, predicts the interface temperature rise due to convective and conductive heat transfer between the solid and the gas, both with specified thermal conductivity. The second analysis, developed by Hansen, et al. (ref. 11) predicts the integral of thermal conductivity of the gas at the initial uniform temperature for a given interface temperature rise. The last analysis is based on the premise that the heat transfer is solely conductive. Both methods are outlined in the following paragraphs.

Thomson's approach is to start with a gas of known thermal conductivity, which must satisfy both the continuity equation and the energy equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u) = 0 \tag{56}$$

$$c_p \rho \frac{dT}{dt} = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) \tag{57}$$

where u is the mass-weighted average velocity of the gas mixture at the point x. A transformation is then made to the new variables φ, y, ψ, and ξ which are defined as follows. The quantity φ, the integral of thermal conductivity, is defined as

$$\varphi = \int_0^T k \, dT \tag{58}$$

and can be obtained by integration of figure 13. The quantity y, the dimensionless time-distance parameter, is defined as

$$y = \frac{x}{\sqrt{4a_o t}} \tag{59}$$

where a_o is an arbitrary, fixed reference value of the diffusivity $k/(\rho c_p)$. Furthermore, the solution may be given as functions of ψ and ξ

$$\xi = \frac{d\varphi}{dy} \tag{60}$$

and

$$\psi(y) = \frac{ut}{x} \tag{61}$$

It should be pointed out that setting ψ equal to zero corresponds to assuming heat transfer by conduction only. Substitution of the quantities defined in equations (58) through (61) into the energy equation (eq. (57)) results in

$$\frac{a}{a_o} \frac{d\xi}{dy} = 2y\xi(2\psi - 1) \tag{62}$$

By use of the same transformation the continuity equation (eq. (56)) becomes

$$\frac{d\psi}{dy} + \frac{\psi}{y} = -\frac{1}{2\rho} \frac{d\rho}{d\varphi}(2\psi - 1)\xi \tag{63}$$

The equilibrium quantities $k(T)$ (eqs. (48) and (50)), $c_p(T)$ (eq. (30)), and $\rho(T)$ (eq. (24)) are easily converted through the variation of $\varphi = \varphi(T)$ (eq. (58)) to $a(\varphi)$ and $\rho(\varphi)$. The easiest method of solving the differential equations (60), (62), and (63) is to arbitrarily choose values of ΔT and p, evaluate the various boundary conditions, then numerically integrate the equations. The solution gives $\varphi(T_\infty)$, ξ, and y as functions of ΔT_o and p. The result of the analysis is shown in figure 20, in the form of T_∞, the initial equilibrium gas temperature behind the reflected shock, versus ΔT_o, the interface temperature rise. Two cases are shown in figure 20, the total ΔT_o and the component of ΔT_o due to conduction, $(\Delta T_o)_{\psi=o}$.

The approach described by Hansen (ref. 11) is to start with a gas whose thermal conductivity need not be known. The gas must satisfy the energy equation (57), which can be expressed in terms of the integral of thermal conductivity as

$$\frac{\partial \varphi}{\partial t} - a \frac{\partial^2 \varphi}{\partial x^2} = 0 \tag{64}$$

A second transformation is then made to the new variables y (eq. (59)) and z

$$z = \frac{\varphi}{\varphi_o} \tag{65}$$

where φ_o is an arbitrary, fixed reference value of the integral of thermal conductivity. Then the partial differential equation (64) becomes the ordinary differential equation

$$\frac{a}{a_o} \frac{d^2 z}{dy^2} + 2y \frac{dz}{dy} = 0 \tag{66}$$

For the high-temperature reacting gas it is assumed that the diffusivity in equation (64) is proportional to the integral of thermal conductivity up to a transition point, φ_c, above which it is a constant a_c. This leveling off of the thermal diffusivity can be attributed to the sudden increase in the component of thermal conductivity due to chemical reaction (fig. 15). The assumed diffusivity is compared in figure 21 with the diffusivity calculated from the theoretical approximations of this report. For the region where a is proportional to φ, the quantity z_o is equal to unity, and equation (66) becomes

$$z \frac{d^2 z}{dy^2} + 2y \frac{dz}{dy} = 0 \tag{67}$$

If the value of the dimensionless heat flux at the interface, $(dz/dy)_o$, is assumed, it becomes relatively easy to integrate numerically equation (67) from z equal to zero to the transition point z_c. Since the diffusivity is assumed constant for $z > z_c$, the solution of equation (66) for this second region can be obtained directly from the expression

$$z = z_c + \sqrt{\frac{\pi z_c}{4}} \left(\frac{dz}{dy}\right)_c \left(\exp \frac{y_c^2}{z_c}\right) \left(\text{erf} \frac{y}{\sqrt{z_c}} - \text{erf} \frac{y_c}{\sqrt{z_c}}\right) \tag{68}$$

The value of z_∞ is easily found from equation (68) by letting y approach ∞. Therefore, this analysis provides a direct relation between the heat-transfer rate at the interface in the form of $(dz/dy)_o$ and the integral of thermal conductivity of the high-temperature gas behind the reflected shock in the form of z_∞. This relationship is shown in figure 22.

Two experimental quantities are required from the shock-tube experiments for the purpose of comparing experimental and theoretical values of the interface temperature rise, ΔT_0, and the integral of thermal conductivity, φ_∞. The first is the initial state of the high-temperature nitrogen behind the reflected shock. The shock-wave speed is obtained by measuring the time interval for the shock to traverse two pressure pickups spaced at a known distance. The state of the nitrogen in the test region is then obtained from the previously calculated state variables behind a reflected shock, which were presented as functions of the shock Mach number. The resultant values of T_∞ are the independent variables for the experimental values of ΔT_0 and φ_∞. The second quantity, the interface temperature rise, is measured by a thin film resistance gage mounted flush with the wall at the end of the shock tube. The theoretical and experimental aspects of this thin film gage are discussed in reference 12. The experimental values of ΔT_0 are obtained directly from this measurement. The measured values of ΔT_0 are also used to obtain experimental values of φ_∞ in the following manner. The ΔT_0 is related to the derivative $(dz/dy)_0$ by equating the conductive heat flux at the interface

$$\frac{\varphi_0}{\sqrt{4a_0 t}} \left(\frac{dz}{dy}\right)_0 = \frac{k_s (\Delta T_0)_{\psi=0}}{\sqrt{\pi a_s t}} \tag{69}$$

where the subscript $\psi = 0$ signifies that the ΔT_0 in this equation corresponds to the component due to conduction only. Therefore the interface temperature rise obtained in the experiment was multiplied by the theoretical ratio of $(\Delta T_0)_{\psi=0}/\Delta T_0$ in order to subtract out the convective component. The resultant derivative $(dz/dy)_0$ in equation (69), in turn, is related to the experimentally determined integral of thermal conductivity φ_∞ through figure 22.

The two analyses for the calculation of the theoretical integral of thermal conductivity are based on the assumption that the gas is completely in equilibrium. There is some question concerning possible nonequilibrium effects at the instant immediately following the reflection of the shock off the end of the tube. Shock tube test intervals were compared with nitrogen relaxation times in reference 11. The comparison shows test intervals several orders of magnitude (50 to 200) larger than relaxation times. Therefore, the relaxation effects can be assumed to be negligible for these experiments.

Discussion of Results

The experimental variation of interface temperature rise, ΔT_0, with initial gas temperature, T_∞, is compared in figure 23 with the theoretical variation determined by the method of reference 27. The experimental integrals of thermal conductivity determined by the method of reference 11

are compared in figure 24 with the theoretical integral. The theoretical integral of thermal conductivity for this comparison is obtained by substitution of the values of the coefficient of thermal conductivity calculated in the previous section into equation (58). Both comparisons, in essence, are indications of the accuracy with which the integral of thermal conductivity has been predicted. The variation of pressure P_3 with increasing temperature T_∞ (i.e., increasing shock strength) for this series of experiments can be seen in the upper margin of both figures. It should be emphasized that the pressures and temperatures behind the reflected shock, P_∞ and T_∞, are not measured directly, but are calculated from the shock relations for a measured value of shock speed.[2] In other words, the experiment is a test of the consistency of both the thermodynamic properties used in calculating shock relations and the thermal conductivity approximations.

The lowest temperature experimental point (910° K) in both comparisons was used for calibration of the film gage, as the values of the thermal properties of the gage (c_p and k) are relatively uncertain. At this test condition the interface temperature jumped approximately 15° K above atmospheric temperature after the reflection of the shock wave. At this temperature where the thermal conductivity has been established, constant values for the thermal diffusivity and product of specific heat and thermal conductivity of the thin film gage were found by equating the experimentally determined ΔT_0 and φ_∞ to the theoretical values. These constants were then used to analyze the data for higher temperature tests where the interface temperature rise, ΔT_0, varied from 30° K to 50° K.

The experimental interface temperature rise is compared in figure 23 with the theoretical values. The agreement is good up to and including the maximum temperature of 6000° K. The experimental integrals of thermal conductivity obtained from the measurements of boundary conditions are compared in figure 24 with the theoretical integral. Both the experimental and theoretical values are presented in dimensionless form $\varphi_\infty/\varphi_\infty^*$, where the φ_∞^* is defined as the integral of thermal conductivity for ideal nitrogen (i.e., translational and rotational degrees of freedom). The expression for φ_∞^* is given by

$$\varphi_\infty^* = \int_0^T k_0 \, dt \qquad (70)$$

where the expression for k_0 is given in equation (50). At temperatures ranging up to 4500° K, the increase in the over-all integral above the ideal gas value of 1.0 can be attributed to vibrational and electronic modes of excitation. Above 4500° K, nitrogen dissociation is initiated, as evidenced by a sudden rise in φ_∞. It was pointed out earlier that the rise is caused by the increase in the component of thermal conductivity due to chemical reaction. The experimental and theoretical $\varphi_\infty/\varphi_\infty^*$ agree

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[2]The quantity P_3 was measured in reference 11 and found to agree with calculated values within a few percent for most cases.

fairly well up to 5000° K. From 5000° K to 6000° K, the experimental $\varphi_\infty/\varphi_\infty{}^*$ is generally higher than the theoretical value by approximately 15 percent. A cluster of experimental points at 6000° K coincides with the theoretical value. This agreement is fortuitous and can be attributed to the fact that the assumed diffusivity was much lower than the theoretical diffusivity at temperatures above 5500° K (fig. 21).

The comparisons of ΔT_0 and φ, in essence, are a direct indication of the accuracy with which the thermodynamic properties and the integral of thermal conductivity for nitrogen have been predicted. The coefficients of thermal conductivity k/k_0 can be derived only from the slope of the temperature versus integral of thermal conductivity (fig. 23). However, the uncertainty of a derivative from any experimental data is relatively large, although it is evident that any discrepancies between experimental and predicted thermal conductivities would be much smaller than the corresponding discrepancies between experimental and predicted integrals of thermal conductivities. In this light, the close correlation between experimental and theoretical estimates of the integral of thermal conductivity can be interpreted as a necessary but not sufficient criterion that the predictions are accurate. The correlation does indicate that the predicted thermodynamic properties and coefficients of thermal conductivity may have suitable accuracy for many engineering needs.

CONCLUDING REMARKS

The thermodynamic and transport properties of equilibrium nitrogen have been estimated over a wide range of pressures and temperatures where dissociation, single ionization, and double ionization occur. It is felt that the theories and parameters required for the calculation of thermodynamic properties are well established, and the resulting values are accurate to the order of 5 percent. In contrast to the exactness of the thermodynamic calculations, the transport properties must be calculated from approximate theories and empirically determined parameters, because of the absence of exact values for the basic parameters of transport properties, the collision integrals. The largest deviation is expected for the thermal conductivity due to collisions. Fortunately, the magnitude of this component of thermal conductivity is negligible except at temperatures and pressures where double ionization occurs. It is estimated that transport properties are predicted within 30 percent.

A comparison was made of thermodynamic and transport properties between air and nitrogen in the region of double ionization. The magnitudes of the air and nitrogen properties which are dependent on ϵ, the fraction of particles which have become doubly ionized, lie within 4 percent of one another. In contrast, the $\partial\epsilon/\partial T$ dependent properties were similar in the peak region only, and were markedly different for points off the peak. However, sufficient comparative air data are included so that off-peak air properties can be determined by interpolation.

The calculated thermodynamic properties of nitrogen were utilized to determine the state variables, pressure, temperature, density, and enthalpy, behind incident and reflected shock waves. These shock properties were applied to the experimental determination of the interface temperature rise and the integral of thermal conductivity. The experimental temperature rise and integral were then compared to the calculated values. The agreement was good. However, a close correlation is a necessary but not sufficient criterion that the coefficient of thermal conductivity and the thermodynamic properties have been accurately predicted. The close correlation does indicate that the predicted coefficients of thermal conductivity and thermodynamic properties may have suitable accuracy for many engineering needs, up to the limits of the test (6000° K).

Ames Research Center
    National Aeronautics and Space Administration
        Moffett Field, Calif., Mar. 22, 1962

APPENDIX A

SHOCK RELATIONS FOR AN IDEAL GAS

1. Incident shock

$$P_{21} = \frac{2\gamma M^2 - (\gamma - 1)}{\gamma + 1}$$

$$\rho_{21} = \frac{(\gamma + 1)M^2}{(\gamma - 1)M^2 + 2}$$

$$T_{21} = P_{21}/\rho_{21}$$

$$h_{21} = P_{21}/\rho_{21}$$

2. Reflected shock

$$P_{32} = \frac{(\alpha + 2)P_{21} - 1}{\alpha + P_{21}}$$

$$\rho_{32} = \frac{(1 + \alpha P_{32})}{(\alpha + P_{32})}$$

$$T_{32} = P_{32}/\rho_{32}$$

$$h_{32} = P_{32}/\rho_{32}$$

where

$$\alpha = \frac{1 + \gamma}{1 - \gamma}$$

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TABLE I.- CONSTANTS FOR PARTITION FUNCTIONS FOR COMPONENTS OF NITROGEN

Particle - N_2

Rotational constant, $\alpha h^2/8\pi^2 Ik = 5.7866°$ K

Vibration constant, $h\nu/k = 3383.8°$ K

Dissociation energy, $D/k = 113,230°$ K

Electronic energy state, $n = 1$; $g_n = 1$; $\epsilon_n = 0°$ K

Particle - N

Ionization energy, $I/k = 168,750°$ K

Electronic energy state, n	g_n	ϵ_n/k, °K
1	4	0
2-3	10	27,656
4-5	6	41,485
6-8	12	119,880
9-15	22	127,590
16-25	46	137,720
26-35	38	147,070
36-45	56	150,760
46-55	50	152,220
56-65	34	156,250

Particle - N^+

Ionization energy, $I/k = 343,590°$ K

Electronic energy state, n	g_n	ϵ_n/k, °K
1	1	0
2	3	70.63
3	5	188.9
4	5	22,031
5	1	47,019
6	5	67,849
7-9	15	132,690
10-12	9	157,110
13	5	207,410
14-17	12	214,410
18-22	21	236,900
23-32	42	257,230
33-41	39	270,960

Particle - N^{++}

Ionization energy, $I/k = 550,420°$ K

Electronic energy state, n	g_n	ϵ_n/k, °K
1	2	0
2	4	251.0
3-5	12	82,398
6-7	10	145,320
8	2	188,440
9-10	6	209,950
11-17	24	305,330
18-27	36	403,980
28-35	34	446,750
36-45	48	459,410
46-54	50	476,800

TABLE II.- EQUILIBRIUM MOL FRACTIONS AND THEIR DERIVATIVES

Parameter	Case I - dissociation $(N_2 \rightarrow 2N)$	Case II - single ionization $(N \rightarrow N^+ + e^-)$	Case III - double ionization $(N^+ \rightarrow N^{++} + e^-)$
Definition of ϵ	ϵ_d = fraction of initial mols of molecules which have become dissociated	ϵ_I = fraction of initial mols of atoms which have become singly ionized	ϵ_{II} = fraction of initial mols of single ions which have become doubly ionized
Compressibility, Z	$Z_d = 1 + \epsilon_d$	$Z_I = 2(1 + \epsilon_I)$	$Z_{II} = 2(2 + \epsilon_{II})$
Partial pressures, $p(A_1)$	$p(N_2) = x(N_2)p = \left(\dfrac{1 - \epsilon_d}{1 + \epsilon_d}\right)p$ $p(N) = x(N)p = \left(\dfrac{2\epsilon_d}{1 + \epsilon_d}\right)p$	$p(N) = x(N)p = \left(\dfrac{1 - \epsilon_I}{1 + \epsilon_I}\right)p$ $p(N^+) = x(N^+)p = \left(\dfrac{\epsilon_I}{1 + \epsilon_I}\right)p$ $p(e^-) = x(e^-)p = \left(\dfrac{\epsilon_I}{1 + \epsilon_I}\right)p$	$p(N^+) = x(N^+)p = \left(\dfrac{1 - \epsilon_{II}}{2 + \epsilon_{II}}\right)p$ $p(N^{++}) = x(N^{++})p = \left(\dfrac{\epsilon_{II}}{2 + \epsilon_{II}}\right)p$ $p(e^-) = x(e^-)p = \left(\dfrac{1 + \epsilon_{II}}{2 + \epsilon_{II}}\right)p$
$\epsilon = f(K_p)$	$\epsilon_d = \left(\dfrac{K_p}{4p + K_p}\right)^{1/2}$	$\epsilon_I = \left(1 + \dfrac{p}{K_p}\right)^{-1/2}$	$\epsilon_{II} = \dfrac{1}{2} + \dfrac{1}{2}\left(1 + \dfrac{8K_p}{p + K_p}\right)^{1/2}$
$\left(\dfrac{\partial\epsilon}{\partial T}\right)_p$	$\left(\dfrac{\partial\epsilon_d}{\partial T}\right) = \left(\dfrac{2}{\epsilon_d} + \dfrac{1}{1 - \epsilon_d} - \dfrac{1}{1 + \epsilon_d}\right)^{-1}\dfrac{d\ln K_p}{dT}$	$\left(\dfrac{\partial\epsilon_I}{\partial T}\right) = \left(\dfrac{2}{\epsilon_I} + \dfrac{1}{1 - \epsilon_I} - \dfrac{1}{1 + \epsilon_I}\right)^{-1}\dfrac{d\ln K_p}{dT}$	$\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right) = \left(\dfrac{1}{\epsilon_{II}} + \dfrac{1}{1 + \epsilon_{II}} + \dfrac{1}{1 - \epsilon_{II}} - \dfrac{1}{2 + \epsilon_{II}}\right)^{-1}\dfrac{d\ln K_p}{dT}$
$\left(\dfrac{\partial Zx_i}{\partial T}\right)_p$	$\left[\dfrac{\partial Z_d x(N_2)}{\partial T}\right]_p = -\left(\dfrac{\partial\epsilon_d}{\partial T}\right)_p$ $\left[\dfrac{\partial Z_d x(N)}{\partial T}\right]_p = 2\left(\dfrac{\partial\epsilon_d}{\partial T}\right)_p$	$\left[\dfrac{\partial Z_I x(N)}{\partial T}\right]_p = -2\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_p$ $\left[\dfrac{\partial Z_I x(N^+)}{\partial T}\right]_p = 2\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_p$ $\left[\dfrac{\partial Z_I x(e^-)}{\partial T}\right]_p = 2\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_p$	$\left[\dfrac{\partial Z_{II} x(N^+)}{\partial T}\right]_p = -2\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_p$ $\left[\dfrac{\partial Z_{II} x(N^{++})}{\partial T}\right]_p = 2\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_p$ $\left[\dfrac{\partial Z_{II} x(e^-)}{\partial T}\right]_p = 2\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_p$
Conversion equation	$K_c = K_p\left(\dfrac{pM_0}{\rho Z_d}\right)^{-1}$ $= K_p\left(\dfrac{1 + \epsilon_d}{pM_0}\right)\rho$	$K_c = K_p\left(\dfrac{pM_0}{\rho Z_I}\right)^{-1}$ $= 2K_p\left(\dfrac{1 + \epsilon_I}{pM_0}\right)\rho$	$K_c = K_p\left(\dfrac{pM_0}{\rho Z_{II}}\right)^{-1}$ $= 2K_p\left(\dfrac{2 + \epsilon_{II}}{pM_0}\right)\rho$
$\left(\dfrac{\partial\epsilon}{\partial T}\right)_\rho$	$\left(\dfrac{\partial\epsilon_d}{\partial T}\right)_\rho = \left(\dfrac{2}{\epsilon_d} + \dfrac{1}{1 - \epsilon_d}\right)^{-1}\dfrac{d\ln K_c}{dT}$	$\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_\rho = \left(\dfrac{2}{\epsilon_I} + \dfrac{1}{1 - \epsilon_I}\right)^{-1}\dfrac{d\ln K_c}{dT}$	$\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_\rho = \left(\dfrac{1}{\epsilon_{II}} + \dfrac{1}{1 + \epsilon_{II}} + \dfrac{1}{1 - \epsilon_{II}}\right)^{-1}\dfrac{d\ln K_c}{dT}$
$\left(\dfrac{\partial Zx_i}{\partial T}\right)_\rho$	$\left[\dfrac{\partial Z_d x(N_2)}{\partial T}\right]_\rho = -\left(\dfrac{\partial\epsilon_d}{\partial T}\right)_\rho$ $\left[\dfrac{\partial Z_d x(N)}{\partial T}\right]_\rho = 2\left(\dfrac{\partial\epsilon_d}{\partial T}\right)_\rho$	$\left[\dfrac{\partial Z_I x(N)}{\partial T}\right]_\rho = -2\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_\rho$ $\left[\dfrac{\partial Z_I x(N^+)}{\partial T}\right]_\rho = 2\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_\rho$ $\left[\dfrac{\partial Z_I x(e^-)}{\partial T}\right]_\rho = 2\left(\dfrac{\partial\epsilon_I}{\partial T}\right)_\rho$	$\left[\dfrac{\partial Z_{II} x(N^+)}{\partial T}\right]_\rho = -2\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_\rho$ $\left[\dfrac{\partial Z_{II} x(N^{++})}{\partial T}\right]_\rho = 2\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_\rho$ $\left[\dfrac{\partial Z_{II} x(e^-)}{\partial T}\right]_\rho = 2\left(\dfrac{\partial\epsilon_{II}}{\partial T}\right)_\rho$

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN
(a) Compressibility, Z

T, °K	Pressure, atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1000
293	1.000	1.000	1.000.	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2500	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3000	1.001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
3500	1.011	1.005	1.004	1.002	1.001	1.001	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
4000	1.090	1.040	1.028	1.013	1.009	1.004	1.003	1.001	1.001	1.000	1.000	1.000	1.000	1.000	1.000
4500	1.416	1.200	1.143	1.065	1.046	1.020	1.014	1.006	1.005	1.002	1.001	1.001	1.000	1.000	1.000
5000	1.861	1.603	1.471	1.232	1.166	1.075	1.053	1.024	1.017	1.008	1.005	1.002	1.002	1.001	1.001
5500	1.983	1.912	1.843	1.573	1.443	1.216	1.154	1.070	1.049	1.022	1.016	1.007	1.005	1.002	1.002
6000	2.007	1.988	1.971	1.866	1.773	1.478	1.359	1.169	1.121	1.054	1.038	1.017	1.012	1.005	1.004
6500	2.031	2.011	2.003	1.970	1.937	1.761	1.638	1.347	1.253	1.116	1.082	1.037	1.026	1.012	1.008
7000	2.088	2.039	2.026	2.003	1.990	1.919	1.851	1.584	1.453	1.222	1.159	1.072	1.051	1.023	1.016
7500	2.214	2.096	2.067	2.027	2.015	1.980	1.951	1.791	1.673	1.376	1.276	1.127	1.090	1.041	1.029
8000	2.456	2.208	2.148	2.065	2.045	2.010	1.994	1.912	1.839	1.562	1.433	1.210	1.150	1.068	1.048
8500	2.847	2.409	2.292	2.131	2.092	2.037	2.021	1.972	1.931	1.734	1.605	1.321	1.233	1.106	1.075
9000	3.309	2.722	2.528	2.243	2.172	2.075	2.051	2.006	1.981	1.857	1.756	1.455	1.340	1.159	1.113
9500	3.666	3.117	2.860	2.417	2.298	2.133	2.093	2.033	2.012	1.932	1.864	1.597	1.465	1.228	1.163
10,000	3.855	3.487	3.236	2.663	2.482	2.220	2.156	2.066	2.040	1.978	1.933	1.725	1.594	1.312	1.226
11,000	3.972	3.872	3.765	3.286	3.021	2.513	2.369	2.166	2.116	2.039	2.010	1.898	1.808	1.513	1.388
12,000	3.994	3.968	3.937	3.735	3.554	2.966	2.727	2.343	2.244	2.105	2.068	1.986	1.934	1.709	1.576
13,000	3.999	3.991	3.982	3.912	3.835	3.435	3.177	2.619	2.448	2.203	2.141	2.044	2.005	1.854	1.744
14,000	4.007	3.998	3.994	3.969	3.939	3.741	3.562	2.976	2.735	2.347	2.246	2.102	2.059	1.946	1.867
15,000	4.046	4.008	4.002	3.989	3.976	3.886	3.789	3.334	3.070	2.545	2.392	2.173	2.116	2.008	1.950
16,000	4.201	4.045	4.022	3.999	3.992	3.948	3.900	3.611	3.385	2.789	2.581	2.266	2.186	2.058	2.008
17,000	4.594	4.168	4.089	4.016	4.004	3.977	3.951	3.783	3.624	3.056	2.805	2.384	2.272	2.108	2.056
18,000	5.157	4.466	4.272	4.063	4.030	3.994	3.977	3.880	3.778	3.310	3.045	2.528	2.379	2.163	2.103
19,000	5.604	4.934	4.629	4.181	4.095	4.013	3.996	3.933	3.869	3.520	3.274	2.693	2.505	2.226	2.152
20,000	5.834	5.395	5.090	4.419	4.241	4.052	4.020	3.965	3.923	3.676	3.470	2.872	2.648	2.299	2.207
21,000	5.931	5.702	5.489	4.778	4.500	4.131	4.065-	3.989	3.957	3.783	3.623	3.054	2.803	2.382	2.269
22,000	5.970	5.859	5.740	5.174	4.851	4.279	4.152	4.018	3.985	3.856	3.735	3.228	2.963	2.476	2.339
23,000	5.986	5.933	5.871	5.501	5.216	4.511	4.301	4.062	4.016	3.906	3.815	3.383	3.120	2.578	2.415
24,000	5.993	5.967	5.935	5.719	5.512	4.807	4.522	4.135	4.060	3.945	3.873	3.515	3.267	2.686	2.499
25,000	5.997	5.983	5.966	5.843	5.713	5.119	4.797	4.250	4.129	3.980	3.918	3.622	3.397	2.799	2.588
26,000	5.998	5.991	5.982	5.913	5.833	5.394	5.087	4.414	4.233	4.019	3.957	3.709	3.511	2.914	2.683
27,000	5.999	5.995	5.990	5.950	5.903	5.602	5.348	4.624	4.379	4.069	3.996	3.778	3.606	3.026	2.778
28,000	5.999	5.997	5.994	5.971	5.942	5.745	5.554	4.861	4.564	4.138	4.043	3.835	3.685	3.135	2.875
29,000	6.000	5.998	5.996	5.982	5.965	5.838	5.703	5.099	4.777	4.231	4.103	3.883	3.752	3.237	2.971
30,000	6.000	5.999	5.998	5.989	5.978	5.896	5.803	5.315	4.998	4.351	4.181	3.930	3.809	3.332	3.064

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN - Continued
(b) Energy, ZE/RT

T, °K	Pressure, atmospheres
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1,000
293	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
500	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51	2.51
1,000	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62	2.62
1,500	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76	2.76
2,000	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88	2.88
2,500	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97	2.97
3,000	3.07	3.05	3.05	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04	3.04
3,500	3.46	3.26	3.21	3.15	3.13	3.11	3.11	3.10	3.10	3.10	3.10	3.09	3.09	3.09	3.09
4,000	5.66	4.27	3.94	3.50	3.39	3.25	3.22	3.17	3.16	3.15	3.14	3.14	3.14	3.14	3.14
4,500	13.59	8.19	6.76	4.79	4.32	3.68	3.53	3.33	3.29	3.22	3.21	3.19	3.18	3.18	3.17
5,000	22.62	16.79	13.82	8.44	6.95	4.90	4.40	3.74	3.58	3.37	3.32	3.25	3.24	3.22	3.21
5,500	23.41	21.95	20.53	14.99	12.32	7.65	6.39	4.66	4.24	3.68	3.55	3.37	3.33	3.27	3.26
6,000	22.32	21.90	21.57	19.58	17.83	12.26	10.02	6.44	5.52	4.27	3.97	3.57	3.47	3.35	3.32
6,500	21.60	21.04	20.85	20.22	19.65	16.57	14.42	9.33	7.69	5.30	4.70	3.91	3.72	3.47	3.41
7,000	21.84	20.57	20.25	19.70	19.45	18.26	17.16	12.80	10.67	6.89	5.87	4.45	4.11	3.65	3.54
7,500	23.69	20.88	20.20	19.25	18.97	18.31	17.85	15.40	13.60	9.05	7.51	5.24	4.67	3.91	3.73
8,000	27.96	22.40	21.04	19.20	18.74	17.99	17.69	16.47	15.41	11.41	9.55	6.33	5.47	4.28	3.99
8,500	34.89	25.64	23.17	19.77	18.94	17.78	17.44	16.63	16.06	13.35	11.59	7.70	6.50	4.77	4.35
9,000	42.52	30.77	26.89	21.19	19.77	17.84	17.35	16.50	16.12	14.47	13.16	9.25	7.74	5.40	4.80
9,500	47.39	36.97	32.08	23.66	21.40	18.28	17.52	16.40	16.02	14.92	14.06	10.74	9.10	6.16	5.36
10,000	48.76	42.10	37.56	27.21	23.94	19.21	18.04	16.41	15.97	15.01	14.45	11.96	10.40	7.05	6.03
11,000	46.85	45.19	43.43	35.53	31.16	22.79	20.41	17.06	16.24	15.00	14.56	13.22	12.23	8.98	7.62
12,000	43.82	43.43	42.97	39.90	37.15	28.24	24.61	18.79	17.28	15.18	14.61	13.51	12.93	10.62	9.25
13,000	41.05	40.92	40.79	39.82	38.73	33.11	29.50	21.65	19.25	15.80	14.93	13.59	13.11	11.56	10.50
14,000	38.79	38.59	38.53	38.19	37.80	35.20	32.86	25.18	22.03	16.95	15.63	13.74	13.20	11.96	11.22
15,000	37.59	36.68	36.54	36.34	36.18	35.08	33.89	28.31	25.07	18.62	16.74	14.06	13.36	12.12	11.55
16,000	39.20	35.64	35.12	34.63	34.53	34.02	33.46	30.12	27.52	20.64	18.23	14.60	13.67	12.23	11.71
17,000	45.79	36.60	34.89	33.33	33.09	32.73	32.45	30.62	28.88	22.69	19.95	15.37	14.15	12.36	11.82
18,000	55.18	41.06	37.10	32.81	32.14	31.48	31.30	30.28	29.23	24.40	21.67	16.32	14.78	12.56	11.94
19,000	61.44	48.40	42.46	33.75	32.08	30.50	30.23	29.57	28.94	25.52	23.11	17.41	15.56	12.83	12.11
20,000	63.11	54.98	49.30	36.85	33.54	30.02	29.45	28.74	28.34	26.03	24.12	18.53	16.44	13.18	12.33
21,000	62.30	58.23	54.45	41.82	36.88	30.34	29.17	27.96	27.63	26.08	24.65	19.59	17.36	13.61	12.60
22,000	60.60	58.72	56.68	47.04	41.54	31.81	29.63	27.40	26.97	25.83	24.80	20.49	18.24	14.10	12.93
23,000	58.68	57.81	56.80	50.74	46.08	34.53	31.11	27.20	26.50	25.42	24.68	21.17	19.03	14.62	13.30
24,000	56.79	56.37	55.87	52.44	49.21	38.09	33.61	27.51	26.35	24.98	24.40	21.61	19.68	15.16	13.71
25,000	54.99	54.79	54.53	52.67	50.68	41.66	36.77	28.45	26.62	24.59	24.06	21.84	20.17	15.70	14.13
26,000	53.31	53.21	53.07	52.06	50.90	44.44	39.94	30.07	27.41	24.37	23.74	21.90	20.49	16.21	14.55
27,000	51.75	51.70	51.62	51.06	50.39	46.12	42.51	32.23	28.76	24.40	23.52	21.85	20.66	16.68	14.97
28,000	50.30	50.27	50.23	49.91	49.52	46.80	44.18	34.64	30.57	24.71	23.49	21.72	20.72	17.08	15.36
29,000	48.95	48.93	48.91	48.72	48.49	46.79	44.99	36.94	32.64	25.36	23.69	21.57	20.70	17.42	15.72
30,000	47.69	47.68	47.66	47.55	47.41	46.34	45.14	38.83	34.72	26.34	24.15	21.45	20.64	17.69	16.05

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN - Continued
(c) Enthalpy, ZH/RT

| T, °K | Pressure, atmospheres |
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1,000
293	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
500	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51	3.51
1,000	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62	3.62
1,500	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76	3.76
2,000	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88	3.88
2,500	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97
3,000	4.07	4.05	4.05	4.04	4.04	4.04	4.04	4.04	4.04	4.04	4.04	4.04	4.04	4.04	4.04
3,500	4.47	4.26	4.21	4.15	4.13	4.11	4.11	4.10	4.10	4.10	4.10	4.10	4.10	4.10	4.10
4,000	6.75	5.31	4.97	4.51	4.40	4.25	4.22	4.17	4.16	4.15	4.14	4.14	4.14	4.14	4.14
4,500	15.01	9.39	7.90	5.85	5.36	4.70	4.55	4.34	4.29	4.22	4.21	4.19	4.18	4.18	4.17
5,000	24.48	18.40	15.29	9.67	8.12	5.97	5.46	4.76	4.60	4.38	4.33	4.26	4.24	4.22	4.21
5,500	25.39	23.87	22.38	16.56	13.76	8.87	7.55	5.73	5.29	4.70	4.56	4.37	4.33	4.27	4.26
6,000	24.32	23.88	23.54	21.45	19.60	13.74	11.38	7.61	6.64	5.32	5.01	4.59	4.49	4.35	4.32
6,500	23.63	23.05	22.86	22.19	21.58	18.33	16.06	10.68	8.94	6.41	5.79	4.95	4.75	4.48	4.42
7,000	23.93	22.61	22.28	21.70	21.44	20.18	19.01	14.39	12.12	8.11	7.02	5.52	5.16	4.67	4.56
7,500	25.91	22.97	22.27	21.27	20.99	20.29	19.80	17.19	15.27	10.43	8.79	6.37	5.77	4.95	4.76
8,000	30.42	24.61	23.19	21.26	20.78	20.00	19.69	18.39	17.24	12.97	10.98	7.54	6.62	5.35	5.04
8,500	37.73	28.05	25.46	21.90	21.04	19.82	19.47	18.60	17.99	15.08	13.19	9.02	7.73	5.88	5.42
9,000	45.83	33.50	29.42	23.43	21.95	19.92	19.40	18.51	18.10	16.33	14.91	10.70	9.08	6.56	5.91
9,500	51.05	40.08	34.94	26.08	23.70	20.42	19.61	18.43	18.04	16.85	15.93	12.34	10.56	7.39	6.52
10,000	52.61	45.58	40.80	29.87	26.42	21.43	20.20	18.48	18.01	16.99	16.38	13.68	12.00	8.36	7.25
11,000	50.82	49.06	47.20	38.81	34.18	25.30	22.78	19.23	18.35	17.03	16.57	15.12	14.04	10.50	9.01
12,000	47.81	47.40	46.91	43.64	40.70	31.20	27.33	21.13	19.53	17.28	16.68	15.50	14.87	12.33	10.82
13,000	45.05	44.92	44.78	43.73	42.56	36.55	32.67	24.27	21.70	18.00	17.07	15.63	15.11	13.42	12.25
14,000	42.80	42.58	42.52	42.16	41.74	38.94	36.42	28.16	24.76	19.30	17.87	15.84	15.26	13.91	13.09
15,000	41.64	40.69	40.54	40.33	40.16	38.96	37.68	31.64	28.14	21.16	19.14	16.24	15.48	14.13	13.50
16,000	43.40	39.68	39.14	38.63	38.52	37.97	37.36	33.73	30.91	23.43	20.81	16.87	15.86	14.29	13.71
17,000	50.39	40.77	38.98	37.35	37.10	36.70	36.40	34.40	32.51	25.75	22.76	17.75	16.42	14.47	13.87
18,000	60.34	45.53	41.37	36.87	36.17	35.48	35.27	34.16	33.01	27.71	24.71	18.85	17.16	14.72	14.05
19,000	67.04	53.34	47.09	37.93	36.18	34.52	34.22	33.50	32.81	29.04	26.39	20.10	18.07	15.06	14.26
20,000	68.95	60.37	54.39	41.27	37.78	34.07	33.47	32.70	32.26	29.71	27.59	21.41	19.09	15.48	14.54
21,000	68.23	63.93	59.94	46.60	41.38	34.47	33.23	31.95	31.59	29.86	28.28	22.65	20.16	15.99	14.87
22,000	66.57	64.57	62.42	52.21	46.40	36.09	33.79	31.41	30.96	29.68	28.54	23.72	21.20	16.57	15.27
23,000	64.67	63.74	62.67	56.24	51.29	39.04	35.41	31.26	30.52	29.33	28.50	24.55	22.15	17.20	15.72
24,000	62.78	62.34	61.81	58.16	54.72	42.90	38.13	31.64	30.41	28.92	28.28	25.12	22.95	17.85	16.21
25,000	60.99	60.77	60.50	58.51	56.39	46.78	41.57	32.70	30.75	28.57	27.98	25.46	23.56	18.50	16.72
26,000	59.31	59.20	59.06	57.97	56.73	49.83	45.03	34.49	31.65	28.39	27.69	25.61	24.00	19.13	17.23
27,000	57.75	57.69	57.61	57.01	56.29	51.72	47.86	36.86	33.14	28.46	27.52	25.63	24.27	19.70	17.74
28,000	56.30	56.27	56.22	55.88	55.46	52.55	49.73	39.50	35.13	28.85	27.53	25.56	24.41	20.21	18.24
29,000	54.95	54.93	54.90	54.70	54.45	52.63	50.69	42.04	37.42	29.59	27.79	25.46	24.46	20.65	18.69
30,000	53.69	53.68	53.67	53.54	53.39	52.24	50.95	44.14	39.72	30.69	28.33	25.38	24.45	21.02	19.11

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN - Continued
(d) Entropy, ZS/R

T, °K							Pressure, atmospheres								
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1000
293	32.2	30.6	29.9	28.3	27.6	26.0	25.3	23.7	23.0	21.3	20.7	19.0	18.4	16.7	16.0
500	34.1	32.5	31.8	30.1	29.4	27.8	27.1	25.5	24.8	23.2	22.5	20.9	20.2	18.6	19.3
1,000	36.6	35.0	34.3	32.7	32.0	30.4	29.7	28.1	27.4	25.6	25.1	23.5	22.8	21.2	20.5
1,500	38.3	36.7	36.0	34.3	33.7	32.0	31.4	29.7	29.0	27.4	26.7	25.1	24.4	22.8	22.1
2,000	39.5	37.9	37.2	35.6	34.9	33.3	32.6	31.0	30.3	28.7	27.9	26.4	25.7	24.1	23.4
2,500	40.4	38.8	38.1	36.5	35.8	34.2	33.5	31.9	31.2	29.6	28.9	27.3	26.6	25.0	24.3
3,000	41.3	39.6	38.9	37.3	36.6	35.0	34.3	32.7	32.0	30.4	29.7	28.1	27.4	25.8	25.1
3,500	42.3	40.5	39.7	38.1	37.4	35.7	35.0	33.4	32.7	31.1	30.4	28.8	28.1	26.5	25.8
4,000	45.3	42.2	41.1	39.0	38.2	36.4	35.7	34.0	33.3	31.7	31.0	29.4	28.7	27.1	26.4
4,500	54.8	47.1	44.8	40.9	39.7	37.4	36.5	34.7	34.0	32.3	31.6	29.9	29.2	27.6	26.9
5,000	66.4	57.5	53.3	45.5	43.2	39.2	38.0	35.6	34.7	32.9	32.1	30.4	29.7	28.1	27.4
5,500	69.7	65.0	62.2	53.7	49.8	42.8	40.7	37.1	35.9	33.6	32.8	31.0	30.2	28.6	27.9
6,000	70.8	67.1	65.4	60.2	57.1	48.6	45.3	39.5	37.8	34.7	33.6	31.6	30.8	29.1	28.3
6,500	72.0	68.2	66.6	62.7	60.8	54.5	51.1	43.3	40.7	36.2	34.8	32.3	31.4	29.5	28.7
7,000	74.1	69.4	67.7	63.9	62.2	57.8	55.3	47.9	44.6	38.5	36.6	33.3	32.2	30.0	29.2
7,500	77.8	71.4	69.2	64.9	63.2	59.3	57.5	51.8	48.7	41.4	38.9	34.5	33.2	30.6	29.7
8,000	84.1	73.1	71.6	66.3	64.4	60.3	58.6	54.2	51.7	44.7	41.7	36.1	34.4	31.4	30.3
8,500	93.4	79.6	75.3	68.2	65.9	61.4	59.6	55.5	53.5	47.7	44.6	38.1	36.0	32.2	31.0
9,000	103.9	86.8	80.9	71.1	68.1	62.6	60.7	56.5	54.7	49.8	47.2	40.4	37.8	33.3	31.8
9,500	111.8	95.3	88.1	75.0	71.0	64.2	61.9	57.4	55.6	51.2	49.0	42.6	39.8	34.5	32.8
10,000	116.0	103.0	95.9	80.3	75.0	66.3	63.5	58.4	56.5	52.2	50.3	44.6	41.8	35.8	33.9
11,000	119.2	111.1	106.6	92.5	85.7	72.4	68.1	61.0	58.6	53.9	52.0	47.4	45.1	38.9	36.4
12,000	120.5	113.6	110.4	100.9	95.5	80.7	74.9	64.6	61.4	55.7	53.6	49.1	47.2	41.7	39.1
13,000	121.4	114.9	112.0	104.5	100.7	88.8	82.6	69.6	65.2	57.8	55.4	50.5	48.6	43.8	41.4
14,000	122.4	115.8	112.9	106.2	103.0	94.0	88.9	75.4	70.0	60.5	57.5	51.9	49.9	45.3	43.2
15,000	124.2	116.7	113.8	107.2	104.2	96.7	92.8	80.9	75.2	63.8	60.0	53.5	51.2	46.5	44.5
16,000	128.7	118.3	115.0	108.0	105.1	98.2	94.9	85.2	79.9	67.5	63.0	55.2	52.6	47.6	45.6
17,000	138.5	121.8	117.2	109.0	106.0	99.2	96.1	87.9	83.4	71.3	66.3	57.1	54.1	48.7	46.6
18,000	151.6	129.0	121.9	110.7	107.2	100.0	97.1	89.6	85.8	74.7	69.6	59.2	55.9	49.8	47.6
19,000	161.7	139.5	130.0	113.8	109.1	101.0	97.9	90.8	87.4	77.6	72.6	61.5	57.7	50.9	48.6
20,000	167.1	149.5	139.9	119.1	112.6	102.3	98.9	91.7	88.5	79.8	75.2	63.9	59.7	52.1	49.6
21,000	169.8	156.1	148.2	126.6	118.2	104.3	100.3	92.5	89.4	81.4	77.3	66.2	61.7	53.4	50.7
22,000	171.3	159.7	153.5	134.5	125.2	107.6	102.4	93.4	90.2	82.6	78.8	68.4	63.7	54.7	51.8
23,000	172.3	161.7	156.6	140.9	132.3	112.2	105.5	94.7	91.1	83.6	80.1	70.3	65.6	56.1	52.9
24,000	173.1	163.0	158.4	145.3	138.0	117.8	109.8	96.4	92.3	84.4	81.0	71.9	67.4	57.5	54.1
25,000	173.8	164.0	159.6	148.0	141.9	123.5	114.9	98.8	93.9	85.2	81.9	73.3	69.0	58.9	55.3
26,000	174.5	164.8	160.5	149.8	144.5	128.5	120.0	101.9	96.1	86.1	82.7	74.5	70.3	60.3	56.4
27,000	175.2	165.4	161.2	151.0	146.2	132.3	124.6	105.6	98.8	87.3	83.5	75.4	71.5	61.6	57.6
28,000	175.8	166.1	161.9	151.9	147.4	135.0	128.3	109.6	102.0	88.7	84.6	76.3	72.5	62.8	58.8
29,000	176.4	166.7	162.5	152.7	148.3	136.9	131.0	113.6	105.6	90.5	85.8	77.0	73.4	64.0	60.0
30,000	177.0	167.3	163.1	153.4	149.1	138.3	133.0	117.2	109.2	92.6	87.3	77.8	74.2	65.0	60.9

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN - Continued
(e) Dimensionless specific heat at constant density, Zc_V/R

T, °K	Pressure, Atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1.0	5	10	50	100	500	1000
293	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
500	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55	2.55
1,000	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92	2.92
1,500	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17	3.17
2,000	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29	3.29
2,500	3.38	3.37	3.37	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36	3.36
3,000	3.90	3.62	3.56	3.47	3.45	3.42	3.42	3.41	3.41	3.40	3.40	3.40	3.40	3.40	3.40
3,500	9.23	6.03	5.27	4.25	4.01	3.69	3.61	3.51	3.48	3.45	3.44	3.43	3.43	3.43	3.43
3,750	18.56	10.27	8.28	5.61	4.97	4.12	3.92	3.65	3.59	3.50	3.46	3.45	3.45	3.44	3.44
4,000	37.41	19.10	14.59	8.47	7.00	5.04	4.57	3.95	3.80	3.60	3.56	3.49	3.48	3.46	3.45
4,250	68.15	35.11	26.24	13.87	10.85	6.78	5.81	4.51	4.20	3.78	3.69	3.56	3.52	3.48	3.47
4,500	99.72	59.34	44.92	23.04	17.45	9.81	7.96	5.48	4.89	4.10	3.91	3.66	3.60	3.52	3.50
4,750	96.93	84.96	68.82	36.93	27.75	14.66	11.44	7.06	6.01	4.60	4.27	3.82	3.72	3.57	3.54
5,000	57.12	90.75	86.45	54.81	41.99	21.88	16.66	9.47	7.72	5.38	4.82	4.07	3.89	3.66	3.60
5,250	25.20	65.57	79.55	71.43	58.27	31.69	23.97	12.93	10.21	6.51	5.62	4.43	4.15	3.77	3.68
5,500	11.20	34.90	52.02	75.95	70.44	43.53	33.34	17.66	13.63	8.08	6.74	4.94	4.51	3.94	3.80
5,750	6.80	16.87	27.50	62.28	69.75	55.14	43.96	23.72	18.10	10.19	8.25	5.62	5.00	4.16	3.96
6,000	7.66	9.03	14.06	40.48	54.81	62.09	53.58	30.94	23.64	12.90	10.20	6.52	5.63	5.00	4.16
6,250	11.09	7.15	8.35	23.24	35.71	59.89	58.55	38.68	30.04	16.25	12.64	7.65	6.44	5.58	4.42
6,500	16.10	8.90	7.51	13.29	21.22	48.84	55.74	45.64	36.75	20.23	15.60	9.05	7.44	5.26	4.74
6,750	23.11	12.39	9.62	8.74	12.74	34.68	45.91	49.88	42.71	24.73	19.05	10.74	8.66	7.16	5.14
7,000	32.79	17.12	13.14	8.00	8.81	22.77	33.58	49.61	46.48	29.47	22.90	12.72	1.01	6.49	5.61
7,250	45.76	23.35	17.76	9.73	8.24	14.78	22.90	44.53	46.71	34.01	25.95	14.99	11.77	9.41	6.17
7,500	62.40	31.48	23.71	12.71	9.88	10.30	15.39	36.34	43.00	37.71	30.90	17.51	13.66	8.17	6.82
7,750	82.60	41.84	31.29	16.49	12.66	8.67	10.91	27.60	36.42	39.83	34.29	20.21	15.75	9.21	7.57
8,000	105.20	54.60	40.75	21.13	16.15	9.19	8.99	20.15	28.84	39.79	36.60	23.00	18.00	10.36	8.40
8,250	127.35	69.67	52.18	26.78	20.34	11.04	9.10	14.66	21.87	37.47	37.35	25.72	20.34	11.63	9.34
8,500	144.14	86.41	65.49	33.58	25.36	13.58	10.56	11.17	16.35	33.30	36.29	28.15	22.68	13.01	10.36
8,750	149.74	103.44	80.17	41.61	31.30	16.60	12.75	9.47	12.48	28.18	33.55	30.08	24.88	14.48	11.47
9,000	140.66	118.37	95.17	50.83	38.22	20.08	15.38	9.30	10.20	22.98	29.63	31.26	26.80	16.01	12.65
9,250	119.17	128.02	108.71	61.07	46.10	24.07	18.38	10.22	9.36	18.36	25.20	31.50	28.25	17.57	13.90
9,500	92.32	129.39	118.44	71.93	54.84	28.61	21.77	11.81	9.66	14.64	20.85	30.74	29.09	19.11	15.18
9,750	67.18	121.29	121.91	82.75	64.15	33.72	25.59	13.77	10.76	11.95	17.02	29.06	29.21	20.57	16.47
10,000	47.38	105.46	117.71	92.53	73.60	39.37	29.83	15.98	12.31	10.28	13.93	26.64	28.55	21.89	17.74
10,500	23.96	66.49	90.37	103.97	90.07	52.00	39.60	21.06	16.16	9.64	10.24	20.79	25.24	23.83	20.06
11,000	13.98	37.27	56.93	98.16	97.22	65.15	50.62	27.04	20.70	11.36	9.61	15.34	20.43	24.43	21.77
11,500	9.88	21.41	33.27	77.34	90.04	76.23	61.71	33.88	25.90	14.07	10.99	11.51	15.69	23.46	22.54
12,000	8.14	13.79	20.17	53.18	71.59	81.73	70.86	41.35	31.74	17.21	13.29	9.67	12.06	21.16	22.16
12,500	7.37	10.21	13.55	34.43	50.83	79.04	75.55	48.90	38.00	20.67	15.95	9.56	9.95	18.12	20.69
13,000	7.21	8.48	10.27	22.55	34.26	68.72	73.89	55.69	44.32	24.42	18.85	10.59	9.34	15.00	18.45
13,500	8.30	7.63	8.60	15.70	23.23	54.57	66.07	60.64	50.12	28.40	21.95	12.18	9.84	12.33	15.89
14,000	11.60	7.43	7.74	11.87	16.52	40.81	54.57	62.69	54.68	32.51	25.21	14.00	10.99	10.42	13.45
14,500	18.72	8.52	7.57	9.71	12.58	29.81	42.57	61.22	57.23	36.55	28.57	15.94	12.45	9.37	11.43
15,000	32.75	11.69	8.72	8.48	10.25	21.97	32.25	56.44	57.23	40.27	31.93	17.95	14.03	9.10	10.00
16,000	94.02	29.11	17.99	8.27	8.14	13.26	18.76	45.64	41.48	49.76	37.96	22.12	17.36	10.16	9.04
17,000	175.00	73.81	44.82	14.41	9.85	9.57	12.29	27.39	37.11	46.48	41.87	26.25	20.77	12.11	9.87
18,000	185.31	138.15	96.41	31.57	19.17	8.68	9.38	18.14	25.66	42.30	42.35	29.94	24.08	14.25	11.46
19,000	119.89	169.48	148.08	65.05	39.96	12.69	9.28	12.90	17.85	34.95	39.19	32.67	27.02	16.37	13.22
20,000	60.29	138.44	155.97	108.03	74.01	23.94	14.47	10.16	13.13	27.16	33.56	33.98	29.28	18.39	14.95
21,000	30.87	84.70	117.64	136.25	110.54	43.70	26.38	9.87	10.53	20.70	27.25	33.61	30.58	20.24	16.58
22,000	18.88	46.82	71.85	130.97	129.45	70.47	45.35	13.86	10.20	16.00	21.62	31.68	30.73	21.83	18.07
23,000	14.16	27.46	41.62	100.26	120.30	96.29	69.12	23.01	13.71	12.84	17.20	28.65	29.75	23.07	19.36
24,000	12.28	18.58	25.85	66.64	92.57	110.46	90.98	36.72	21.81	11.12	14.00	25.12	27.85	23.89	20.41
25,000	11.51	14.58	18.27	42.55	63.50	107.39	103.02	53.48	33.76	11.46	11.97	21.63	25.37	24.27	21.20
26,000	11.21	12.76	14.66	28.30	42.15	90.65	101.23	70.15	48.16	14.91	11.48	18.51	22.66	24.19	21.69
27,000	11.11	11.92	12.93	20.52	28.93	69.20	88.02	82.71	62.70	21.61	13.32	15.93	20.03	23.70	21.88
28,000	11.09	11.54	12.09	16.36	21.37	50.22	69.86	88.03	74.45	30.71	18.01	13.96	17.64	22.88	21.80
29,000	11.11	11.36	11.67	14.13	17.07	36.31	52.66	85.33	80.95	41.01	25.11	12.78	15.64	21.80	21.46
30,000	11.14	11.29	11.47	12.92	14.68	27.09	39.18	76.33	81.13	51.17	33.63	12.74	14.11	20.58	20.93

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN - Continued
(f) Dimensionless specific heat at constant pressure, Zc_p/R

T, °K	Pressure, atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1000
293	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
500	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55	3.55
1,000	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92	3.92
1,500	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17	4.17
2,000	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29	4.29
2,500	4.38	4.37	4.37	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36	4.36
3,000	4.93	4.64	4.57	4.48	4.45	4.42	4.42	4.41	4.41	4.40	4.40	4.40	4.40	4.40	4.40
3,500	10.64	7.20	6.39	5.30	5.05	4.70	4.62	4.51	4.49	4.45	4.45	4.43	4.43	4.43	4.43
3,750	20.89	11.80	9.65	6.77	6.08	5.17	4.96	4.67	4.60	4.51	4.49	4.46	4.45	4.44	4.44
4,000	42.43	21.60	16.59	9.88	8.29	6.16	5.66	4.99	4.83	4.61	4.56	4.50	4.48	4.46	4.45
4,250	80.07	40.10	29.83	15.86	12.52	8.06	7.00	5.59	5.26	4.81	4.70	4.56	4.53	4.48	4.47
4,500	121.62	69.93	52.18	26.33	19.97	11.41	9.38	6.66	6.01	5.15	4.95	4.67	4.61	4.52	4.50
4,750	117.88	103.72	82.81	42.96	32.02	16.90	13.27	8.40	7.25	5.71	5.34	4.85	4.74	4.58	4.55
5,000	67.34	111.64	106.69	65.68	49.56	25.32	19.27	11.11	9.16	6.57	5.95	5.13	4.93	4.67	4.61
5,250	29.78	78.72	97.45	88.08	70.85	37.26	27.96	15.08	11.98	7.83	6.85	5.53	5.22	4.80	4.70
5,500	13.98	41.29	62.20	94.47	87.61	52.45	39.61	20.64	15.95	9.62	8.11	6.10	5.62	4.98	4.83
5,750	9.06	20.43	32.75	76.24	86.83	68.15	53.50	28.03	21.28	12.05	9.83	6.87	6.17	5.23	5.01
6,000	9.93	11.58	17.28	48.67	67.08	77.97	66.72	37.21	28.13	15.24	12.10	7.89	6.89	5.56	5.24
6,250	13.62	9.42	10.81	28.00	43.07	75.12	73.84	47.53	36.37	19.30	15.01	9.20	7.82	5.97	5.53
6,500	19.10	11.27	9.80	16.47	25.73	60.42	70.14	57.21	45.38	24.26	18.61	10.85	8.99	6.50	5.91
6,750	26.86	15.07	12.05	11.24	15.86	42.35	57.04	63.35	53.74	30.07	22.94	12.87	10.42	7.14	6.36
7,000	37.77	20.28	15.91	10.34	11.32	27.79	41.22	63.17	59.23	36.44	27.93	15.29	12.15	7.92	6.92
7,250	52.72	27.25	21.03	12.20	10.60	18.32	28.06	59.30	59.74	42.78	33.39	18.13	14.20	8.85	7.57
7,500	72.50	36.51	27.73	15.48	12.37	13.08	19.08	45.44	54.73	48.13	38.89	21.37	16.57	9.94	8.35
7,750	97.38	48.57	36.41	19.70	15.44	11.13	13.80	34.24	45.90	51.33	43.79	24.96	19.26	11.20	9.25
8,000	126.36	63.84	47.47	24.94	19.35	11.65	11.51	24.99	36.03	51.44	47.24	28.78	22.24	12.64	10.27
8,250	155.86	82.45	61.23	31.44	24.11	13.68	11.56	18.34	27.24	48.28	48.48	32.61	25.42	14.26	11.43
8,500	178.92	103.89	77.73	39.42	29.90	16.54	13.16	14.15	20.45	42.63	47.11	36.16	28.70	16.05	12.73
8,750	186.79	126.50	96.56	49.05	36.88	19.97	15.63	12.10	15.76	35.80	43.36	39.05	31.87	18.00	14.16
9,000	174.53	146.96	116.47	60.40	45.19	23.98	18.62	11.83	13.00	29.05	38.05	40.89	34.71	20.08	15.72
9,250	146.12	160.55	135.04	73.38	54.89	28.65	22.09	12.84	11.95	23.18	32.15	41.39	36.94	22.25	17.39
9,500	111.90	162.69	148.75	87.59	65.93	34.06	26.06	14.63	12.25	18.54	26.50	40.42	38.30	24.44	19.16
9,750	81.01	151.79	153.88	102.18	78.06	40.27	30.59	16.88	13.47	15.22	21.62	38.10	38.59	26.58	20.98
10,000	57.41	130.75	148.31	115.76	90.74	47.30	35.75	19.46	15.25	13.16	17.74	34.78	37.75	28.57	22.81
10,500	30.26	81.23	112.07	132.33	113.77	63.60	47.98	25.49	19.75	12.29	13.14	26.89	33.19	31.61	26.27
11,000	18.93	46.01	69.94	124.82	124.46	81.48	62.42	32.83	25.20	14.25	12.29	19.77	26.65	32.71	28.97
11,500	14.30	27.54	41.49	97.14	115.00	97.33	77.72	41.55	31.65	17.46	13.88	14.88	20.37	31.49	30.32
12,000	12.34	18.80	26.18	66.32	90.45	105.75	90.99	51.45	39.15	21.27	16.60	12.52	15.66	28.29	29.94
12,500	11.46	14.71	18.56	43.34	63.84	102.52	98.27	61.93	47.52	25.58	19.85	12.32	12.95	24.08	27.93
13,000	11.26	12.74	14.79	29.20	43.38	88.62	96.46	71.79	56.33	30.41	23.48	13.53	12.12	19.84	24.80
13,500	12.43	11.76	12.88	21.16	30.13	69.88	85.93	79.36	64.78	35.71	27.48	15.46	12.69	16.27	21.25
14,000	16.01	11.52	11.89	16.70	22.19	52.22	70.55	82.85	71.73	41.36	31.82	17.73	14.09	13.74	17.91
14,500	23.78	12.68	11.67	14.20	17.57	38.51	54.90	81.22	75.93	47.14	36.44	20.20	15.89	12.34	15.18
15,000	39.29	16.13	12.76	12.76	14.85	28.93	41.81	74.80	76.41	52.68	41.20	22.83	17.90	11.94	13.26
16,000	109.93	35.42	23.08	12.44	12.37	18.49	25.18	54.65	66.44	61.18	50.26	28.49	22.27	13.20	11.89
17,000	211.02	86.93	53.35	19.19	14.17	14.10	17.38	36.35	49.37	63.23	56.67	34.44	26.98	15.68	12.88
18,000	225.52	166.50	114.77	38.51	24.54	12.96	13.87	24.72	34.41	57.75	58.11	40.10	31.80	18.50	14.90
19,000	143.85	208.21	180.98	77.77	48.33	17.37	13.63	18.25	24.49	47.66	54.04	44.63	36.35	21.42	17.22
20,000	73.14	168.86	192.35	131.44	89.19	30.12	19.39	14.87	18.60	37.13	46.28	47.16	40.12	24.33	19.59
21,000	39.45	102.71	143.70	169.11	135.89	53.26	33.03	14.37	15.35	28.58	37.64	47.15	42.57	27.13	21.92
22,000	25.93	58.02	87.75	162.99	161.70	86.16	55.53	18.81	14.78	22.47	30.05	44.71	43.31	29.69	24.15
23,000	20.62	35.75	52.16	123.86	150.33	119.79	85.11	29.38	18.69	18.40	24.20	40.55	42.28	31.84	26.20
24,000	18.49	25.64	33.98	82.41	114.96	139.39	113.87	45.73	28.08	16.12	19.99	35.62	39.78	33.44	28.00
25,000	17.62	21.11	25.31	53.65	79.00	135.98	130.65	66.56	42.38	16.32	17.30	30.76	36.34	34.40	29.46
26,000	17.27	19.03	21.20	36.98	53.37	114.36	128.92	88.32	60.30	20.21	16.47	26.44	32.53	34.67	30.53
27,000	17.14	18.07	19.22	27.97	37.81	87.13	111.80	105.54	79.24	28.13	18.47	22.88	28.81	34.28	31.18
28,000	17.11	17.62	18.25	23.17	28.96	63.67	88.54	113.38	95.28	39.22	23.95	20.15	25.46	33.31	31.39
29,000	17.12	17.41	17.77	20.61	24.02	46.87	67.03	110.22	104.66	52.24	32.53	18.43	22.63	31.90	31.19
30,000	17.15	17.32	17.53	19.21	21.26	35.89	50.54	98.49	105.42	65.59	43.18	18.12	20.43	30.20	30.63

TABLE III.- THERMODYNAMIC PROPERTIES OF NITROGEN - Concluded
(g) Dimensionless speed of sound, $a^2\rho/p$

T, °K	Pressure, atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1.0	5	10	50	100	500	1,000
293	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400	1.400
500	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392	1.392
1,000	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343	1.343
1,500	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316
2,000	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304	1.304
2,500	1.296	1.297	1.297	1.297	1.297	1.298	1.298	1.298	1.298	1.298	1.298	1.298	1.298	1.298	1.298
3,000	1.263	1.279	1.283	1.289	1.291	1.293	1.293	1.294	1.294	1.294	1.294	1.294	1.294	1.294	1.294
3,500	1.147	1.192	1.211	1.247	1.258	1.276	1.280	1.286	1.288	1.290	1.291	1.292	1.292	1.292	1.292
3,750	1.107	1.141	1.159	1.203	1.221	1.253	1.263	1.278	1.281	1.287	1.288	1.290	1.290	1.291	1.291
4,000	1.090	1.109	1.121	1.159	1.178	1.220	1.236	1.262	1.270	1.281	1.283	1.287	1.288	1.289	1.290
4,250	1.085	1.095	1.102	1.127	1.142	1.184	1.202	1.239	1.251	1.271	1.276	1.284	1.285	1.288	1.288
4,500	1.088	1.091	1.095	1.110	1.120	1.152	1.170	1.211	1.227	1.256	1.265	1.278	1.281	1.286	1.287
4,750	1.095	1.093	1.094	1.102	1.108	1.131	1.145	1.183	1.201	1.238	1.250	1.269	1.275	1.282	1.284
5,000	1.132	1.099	1.098	1.100	1.104	1.118	1.128	1.160	1.177	1.217	1.232	1.259	1.266	1.278	1.281
5,250	1.158	1.112	1.106	1.103	1.104	1.113	1.119	1.143	1.157	1.196	1.212	1.245	1.256	1.272	1.277
5,500	1.248	1.141	1.123	1.108	1.107	1.111	1.115	1.132	1.144	1.177	1.194	1.230	1.243	1.265	1.271
5,750	1.329	1.199	1.158	1.119	1.114	1.113	1.115	1.126	1.135	1.163	1.178	1.215	1.230	1.257	1.265
6,000	1.303	1.279	1.220	1.139	1.126	1.117	1.117	1.124	1.130	1.152	1.165	1.201	1.217	1.247	1.257
6,250	1.233	1.314	1.290	1.174	1.147	1.124	1.122	1.124	1.128	1.144	1.156	1.188	1.204	1.237	1.249
6,500	1.181	1.273	1.304	1.228	1.183	1.135	1.129	1.126	1.128	1.141	1.149	1.178	1.193	1.227	1.240
6,750	1.149	1.218	1.260	1.280	1.234	1.153	1.140	1.130	1.131	1.139	1.146	1.170	1.183	1.217	1.231
7,000	1.129	1.178	1.211	1.290	1.278	1.181	1.157	1.136	1.134	1.139	1.144	1.164	1.176	1.208	1.222
7,250	1.116	1.152	1.176	1.258	1.284	1.219	1.183	1.145	1.140	1.140	1.144	1.159	1.170	1.200	1.214
7,500	1.109	1.135	1.152	1.218	1.256	1.257	1.217	1.157	1.148	1.143	1.145	1.157	1.166	1.193	1.207
7,750	1.105	1.124	1.137	1.187	1.220	1.276	1.251	1.174	1.158	1.147	1.147	1.156	1.163	1.188	1.201
8,000	1.104	1.117	1.127	1.165	1.191	1.266	1.271	1.197	1.173	1.152	1.150	1.156	1.162	1.183	1.195
8,250	1.104	1.113	1.121	1.150	1.170	1.241	1.268	1.224	1.192	1.159	1.155	1.157	1.161	1.180	1.191
8,500	1.106	1.112	1.117	1.139	1.155	1.214	1.247	1.249	1.215	1.168	1.161	1.159	1.162	1.177	1.187
8,750	1.110	1.112	1.116	1.133	1.145	1.192	1.223	1.265	1.239	1.179	1.168	1.161	1.163	1.176	1.185
9,000	1.115	1.113	1.116	1.128	1.138	1.176	1.202	1.265	1.258	1.193	1.177	1.165	1.166	1.175	1.183
9,250	1.122	1.116	1.117	1.126	1.134	1.164	1.185	1.253	1.266	1.210	1.189	1.169	1.168	1.176	1.182
9,500	1.133	1.119	1.119	1.125	1.131	1.156	1.173	1.236	1.261	1.229	1.203	1.175	1.172	1.176	1.182
9,750	1.149	1.125	1.122	1.125	1.130	1.150	1.164	1.218	1.248	1.246	1.218	1.181	1.176	1.178	1.182
10,000	1.172	1.132	1.127	1.126	1.130	1.146	1.157	1.204	1.233	1.260	1.235	1.189	1.181	1.179	1.183
10,500	1.244	1.156	1.142	1.132	1.132	1.142	1.150	1.183	1.206	1.265	1.262	1.208	1.195	1.185	1.186
11,000	1.345	1.199	1.168	1.141	1.138	1.142	1.147	1.171	1.188	1.267	1.267	1.233	1.212	1.192	1.191
11,500	1.443	1.267	1.213	1.155	1.148	1.145	1.148	1.164	1.177	1.226	1.253	1.258	1.234	1.202	1.198
12,000	1.513	1.352	1.279	1.179	1.163	1.150	1.151	1.162	1.172	1.209	1.235	1.273	1.257	1.214	1.206
12,500	1.554	1.435	1.359	1.216	1.186	1.159	1.157	1.162	1.169	1.199	1.220	1.275	1.274	1.229	1.216
13,000	1.562	1.499	1.435	1.268	1.220	1.171	1.165	1.165	1.170	1.192	1.209	1.265	1.280	1.245	1.229
13,500	1.501	1.540	1.495	1.331	1.267	1.188	1.176	1.169	1.172	1.189	1.202	1.252	1.275	1.263	1.243
14,000	1.384	1.549	1.535	1.397	1.324	1.211	1.191	1.175	1.175	1.188	1.198	1.240	1.265	1.278	1.258
14,500	1.268	1.494	1.542	1.456	1.384	1.243	1.211	1.183	1.181	1.188	1.197	1.231	1.254	1.287	1.273
15,000	1.188	1.387	1.486	1.502	1.441	1.283	1.238	1.193	1.187	1.190	1.197	1.225	1.245	1.290	1.284
16,000	1.123	1.207	1.285	1.507	1.516	1.378	1.311	1.222	1.207	1.198	1.200	1.219	1.233	1.279	1.292
17,000	1.112	1.138	1.169	1.342	1.450	1.465	1.399	1.266	1.236	1.210	1.208	1.218	1.227	1.264	1.283
18,000	1.117	1.121	1.131	1.208	1.285	1.492	1.472	1.326	1.227	1.220	1.221	1.221	1.227	1.253	1.269
19,000	1.137	1.123	1.124	1.153	1.188	1.385	1.471	1.394	1.333	1.250	1.236	1.227	1.230	1.247	1.259
20,000	1.183	1.135	1.130	1.137	1.151	1.258	1.358	1.451	1.393	1.280	1.257	1.236	1.235	1.244	1.252
21,000	1.264	1.162	1.145	1.136	1.141	1.190	1.249	1.454	1.442	1.318	1.283	1.248	1.243	1.244	1.249
22,000	1.366	1.212	1.176	1.143	1.142	1.162	1.192	1.375	1.446	1.361	1.315	1.262	1.253	1.247	1.249
23,000	1.453	1.268	1.226	1.159	1.150	1.154	1.168	1.281	1.380	1.403	1.351	1.279	1.265	1.252	1.250
24,000	1.504	1.373	1.301	1.187	1.167	1.154	1.160	1.222	1.295	1.429	1.388	1.299	1.280	1.258	1.254
25,000	1.529	1.443	1.378	1.231	1.194	1.161	1.161	1.192	1.236	1.419	1.415	1.321	1.296	1.266	1.259
26,000	1.539	1.489	1.442	1.289	1.234	1.174	1.167	1.179	1.204	1.369	1.419	1.346	1.315	1.275	1.266
27,000	1.543	1.514	1.484	1.352	1.287	1.193	1.178	1.176	1.189	1.307	1.390	1.370	1.334	1.286	1.274
28,000	1.542	1.527	1.508	1.410	1.345	1.351	1.195	1.178	1.184	1.259	1.339	1.390	1.354	1.297	1.282
29,000	1.541	1.532	1.521	1.454	1.399	1.259	1.220	1.184	1.184	1.229	1.290	1.401	1.372	1.309	1.292
30,000	1.539	1.534	1.527	1.484	1.442	1.303	1.252	1.194	1.189	1.213	1.254	1.397	1.387	1.322	1.302

TABLE IV.- TRANSPORT PROPERTIES FOR NITROGEN
(a) Viscosity ratio, η/η_o

T, °K	Pressure, atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1.000
293	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
500	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
1500	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2500	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3000	1.0001	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3500	1.0013	1.0006	1.0004	1.0001	1.0001	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
4000	1.0136	1.0064	1.0045	1.0021	1.0015	1.0007	1.0005	1.0002	1.0002	1.0001	1.0001	1.0000	1.0000	1.0000	1.0000
4500	1.0656	1.0359	1.0265	1.0126	1.0090	1.0041	1.0029	1.0021	1.0009	1.0004	1.0003	1.0001	1.0001	1.0000	1.0000
5000	1.1362	1.1067	1.0886	1.0491	1.0364	1.0173	1.0124	1.0056	1.0040	1.0018	1.0013	1.0006	1.0004	1.0002	1.0001
5500	1.1785	1.1701	1.1612	1.1215	1.0990	1.0532	1.0391	1.0184	1.0131	1.0060	1.0042	1.0019	1.0013	1.0006	1.0004
6000	1.2068	1.2084	1.2063	1.1904	1.1753	1.1201	1.0943	1.0479	1.0348	1.0161	1.0115	1.0052	1.0037	1.0016	1.0012
6500	1.2212	1.2332	1.2359	1.2339	1.2284	1.1955	1.1702	1.1018	1.0767	1.0370	1.0266	1.0121	1.0086	1.0039	1.0027
7000	1.2127	1.2442	1.2520	1.2627	1.2633	1.2507	1.2366	1.1748	1.1410	1.0740	1.0541	1.0251	1.0179	1.0081	1.0057
7500	1.1576	1.2341	1.2525	1.2779	1.2844	1.2880	1.2824	1.2447	1.2146	1.1298	1.0979	1.0471	1.0338	1.0154	1.0109
8000	1.0213	1.1850	1.2251	1.2796	1.2929	1.3117	1.3139	1.2974	1.2781	1.1988	1.1579	1.0810	1.0588	1.0271	1.0193
8500	.7785	1.0730	1.1517	1.2600	1.2862	1.3226	1.3319	1.3352	1.3255	1.2676	1.2268	1.1282	1.0949	1.0447	1.0320
9000	.4764	.8787	1.0117	1.2073	1.2558	1.3220	1.3385	1.3601	1.3598	1.3253	1.2928	1.1872	1.1430	1.0697	1.0501
9500	.2359	.6189	.7984	1.1078	1.1908	1.3054	1.3334	1.3728	1.3815	1.3702	1.3481	1.2523	1.2012	1.1033	1.0749
10000	.1060	.3677	.5458	.9521	1.0805	1.2664	1.3124	1.3758	1.3919	1.4036	1.3918	1.3160	1.2646	1.2102	1.1072
11000	.0245	.0986	.1768	.5280	.7222	1.0943	1.2001	1.3489	1.3856	1.4370	1.4466	1.4197	1.3833	1.2533	1.1951
12000	.0097	.0295	.0529	.2060	.3432	.7868	.9675	1.2573	1.3325	1.4369	1.4632	1.4868	1.4720	1.3706	1.3052
13000	.0065	.0133	.0208	.0756	.1360	.4467	.6468	1.0805	1.2132	1.4045	1.4523	1.5180	1.5269	1.4729	1.4169
14000	.0063	.0087	.0119	.0331	.0574	.2165	.3596	.8273	1.0195	1.3294	1.4103	1.5235	1.5507	1.5507	1.5131
15000	.0066	.0079	.0089	.0187	.0295	.1044	.1839	.5570	.7734	1.2041	1.3296	1.5086	1.5535	1.6019	1.5874
16000	.0058	.0082	.0090	.0128	.0184	.0559	.0972	.3411	.5303	1.0311	1.2063	1.4711	1.5386	1.6291	1.6381
17000	.0038	.0075	.0089	.0115	.0136	.0342	.0567	.2030	.3402	.8266	1.0449	1.4077	1.5045	1.6394	1.6677
18000	.0022	.0055	.0074	.0115	.0129	.0230	.0367	.1246	.2150	.6275	.8607	1.3171	1.4491	1.6371	1.6822
19000	.0014	.0035	.0052	.0104	.0126	.0182	.0254	.0813	.1397	.4556	.6769	1.2012	1.3716	1.6230	1.6855
20000	.0011	.0022	.0034	.0082	.0110	.0171	.0206	.0559	.0952	.3252	.5147	1.0659	1.2733	1.5963	1.6791
21000	.0010	.0017	.0023	.0058	.0086	.0161	.0194	.0397	.0673	.2336	.3853	.9211	1.1502	1.5568	1.6630
22000	.0011	.0014	.0018	.0041	.0062	.0141	.0180	.0309	.0486	.1713	.2887	.7779	1.0325	1.5043	1.6367
23000	.0011	.0014	.0016	.0030	.0044	.0113	.0157	.0273	.0375	.1282	.2191	.6458	.9039	1.4397	1.6004
24000	.0012	.0014	.0015	.0024	.0033	.0086	.0127	.0252	.0324	.0969	.1687	.5312	.7798	1.3645	1.5543
25000	.0013	.0014	.0016	.0022	.0028	.0065	.0099	.0227	.0296	.0736	.1308	.4358	.6661	1.2809	1.4992
26000	.0014	.0015	.0016	.0021	.0025	.0051	.0077	.0194	.0267	.0581	.1014	.3585	.5660	1.1919	1.4362
27000	.0014	.0016	.0017	.0021	.0024	.0042	.0061	.0161	.0233	.0491	.0796	.2960	.4803	1.1002	1.3670
28000	.0015	.0017	.0018	.0021	.0024	.0037	.0050	.0131	.0197	.0436	.0651	.2449	.4081	1.0089	1.2933
29000	.0016	.0018	.0019	.0022	.0024	.0034	.0044	.0107	.0164	.0392	.0562	.2020	.3471	.9204	1.2169
30000	.0017	.0019	.0020	.0023	.0025	.0033	.0040	.0089	.0136	.0349	.0500	.1658	.2949	.8364	1.1396

TABLE IV.- TRANSPORT PROPERTIES FOR NITROGEN - Continued
(b) Thermal conductivity ratio, k/k_O

T, °K	Pressure, atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1,000
293	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
500	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
1000	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
1500	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14
2000	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
2500	1.19	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18
3000	1.40	1.28	1.26	1.22	1.21	1.20	1.20	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
3500	3.71	2.33	2.00	1.54	1.45	1.31	1.28	1.23	1.22	1.21	1.20	1.20	1.20	1.20	1.20
3750	7.76	4.19	3.32	2.15	1.88	1.50	1.41	1.29	1.27	1.23	1.22	1.21	1.20	1.20	1.20
4000	15.71	8.06	6.11	3.43	2.78	1.91	1.70	1.42	1.36	1.27	1.25	1.22	1.21	1.21	1.20
4250	27.49	14.87	11.18	5.85	4.52	2.70	2.27	1.68	1.54	1.35	1.31	1.25	1.23	1.22	1.21
4500	36.27	24.29	18.87	9.89	7.48	4.08	3.25	2.13	1.86	1.50	1.41	1.29	1.27	1.23	1.22
4750	30.32	32.00	27.40	15.76	11.97	6.30	4.85	2.86	2.38	1.73	1.58	1.37	1.32	1.26	1.24
5000	16.09	30.10	31.15	22.56	17.81	9.53	7.24	3.99	3.19	2.10	1.84	1.49	1.40	1.29	1.27
5250	7.32	19.40	25.34	27.35	23.60	13.74	10.49	5.61	4.36	2.64	2.22	1.66	1.53	1.35	1.31
5500	3.93	10.07	15.25	26.30	26.40	18.40	14.46	7.79	5.96	3.40	2.76	1.91	1.70	1.43	1.36
5750	3.38	5.37	8.16	19.56	23.72	22.20	18.53	10.50	8.03	4.41	3.50	2.24	1.94	1.54	1.44
6000	4.97	3.65	4.75	12.14	17.16	23.29	21.49	13.56	10.52	5.71	4.44	2.69	2.26	1.68	1.54
6250	7.96	4.02	3.68	7.21	10.85	20.71	21.94	16.55	13.23	7.29	5.62	3.25	2.66	1.86	1.67
6500	12.19	6.07	4.48	4.71	6.75	15.80	19.39	18.76	15.82	9.12	7.03	3.95	3.17	2.10	1.84
6750	18.16	9.18	6.73	3.97	4.66	10.92	15.05	19.44	17.73	11.10	8.64	4.79	3.78	2.38	2.04
7000	26.41	13.30	9.90	4.80	4.11	7.38	10.74	18.21	18.39	13.06	10.36	5.76	4.50	2.73	2.29
7250	37.38	18.75	13.98	6.85	5.00	5.29	7.51	15.48	17.50	14.73	12.07	6.86	5.34	3.13	2.58
7500	51.17	25.88	19.27	9.67	7.01	4.45	5.52	12.19	15.31	15.81	13.59	8.06	6.27	3.60	2.92
7750	67.22	34.91	26.01	13.15	9.71	4.78	4.62	9.21	12.50	16.06	14.68	9.30	7.29	4.14	3.31
8000	83.84	45.84	34.35	17.41	12.97	6.17	4.79	6.98	9.79	15.38	15.17	10.51	8.35	4.73	3.76
8250	97.91	58.30	44.28	22.61	16.90	8.28	5.95	5.55	7.59	13.92	14.91	11.61	9.41	5.39	4.25
8500	105.23	71.36	55.46	28.86	21.59	10.85	7.82	4.92	6.05	12.01	13.97	12.50	10.42	6.09	4.78
8750	102.36	83.34	67.15	36.15	27.14	13.81	10.15	5.10	5.21	10.02	12.51	13.06	11.29	6.82	5.36
9000	89.33	91.93	78.05	44.35	33.55	17.22	12.81	6.04	5.06	8.25	10.82	13.22	11.96	7.56	5.97
9250	70.29	94.72	86.37	53.16	40.73	21.12	15.82	7.57	5.62	6.84	9.16	12.97	12.36	8.30	6.59
9500	50.85	90.35	90.20	62.02	48.46	25.55	19.21	9.49	6.78	5.88	7.72	12.32	12.44	8.99	7.23
9750	34.73	79.51	88.20	70.12	56.35	30.50	23.01	11.65	8.38	5.40	6.59	11.38	12.20	9.62	7.85
10000	22.98	64.88	80.41	76.46	63.83	35.90	27.23	14.02	10.26	5.42	5.83	10.28	11.66	10.14	8.44
10500	9.87	36.42	54.90	79.84	74.59	47.51	36.76	19.41	14.56	6.90	5.57	8.06	9.98	10.75	9.43
11000	4.48	18.20	31.08	68.57	74.92	58.50	46.99	25.70	19.51	9.70	6.98	6.42	8.11	10.69	10.04
11500	2.28	9.00	16.26	48.97	63.51	65.93	56.33	32.78	25.15	13.11	9.53	5.75	6.63	9.99	10.14
12000	1.35	4.69	8.52	30.73	46.13	66.84	62.51	40.21	31.35	16.85	12.60	6.23	5.90	8.88	9.74
12500	.94	2.68	4.71	18.14	30.09	60.31	63.38	47.21	37.78	20.92	15.94	7.75	6.11	7.71	8.96
13000	.73	1.72	2.83	10.65	18.62	48.69	58.27	52.75	43.89	25.27	19.50	9.94	7.24	6.74	8.02
13500	.66	1.24	1.89	6.45	11.45	35.97	48.73	55.70	48.94	29.81	23.26	12.44	9.06	6.21	7.14
14000	.67	.97	1.38	4.14	7.23	25.11	37.67	55.27	52.11	34.34	27.15	15.06	11.26	6.23	6.51
14500	.71	.85	1.09	2.85	4.78	17.10	27.58	51.44	52.77	38.58	31.07	17.75	13.60	6.88	6.28
15000	.75	.85	.96	2.10	3.36	11.67	19.64	45.04	50.70	42.21	34.83	20.49	15.99	8.09	6.54
16000	.83	.93	.98	1.37	1.96	5.86	9.96	29.91	40.28	46.25	41.02	26.05	20.84	11.55	8.52
17000	.89	1.01	1.07	1.25	1.45	3.43	5.55	17.99	27.52	44.66	43.91	31.36	25.67	15.45	11.83
18000	.93	1.09	1.16	1.34	1.43	2.31	3.52	10.85	17.58	38.17	42.47	35.78	30.20	19.30	15.52
19000	.93	1.15	1.23	1.43	1.53	1.92	2.52	6.98	11.33	29.67	37.33	38.61	34.04	22.99	19.13
20000	.94	1.17	1.28	1.52	1.63	1.95	2.20	4.87	7.71	21.88	30.41	39.35	36.73	26.48	22.57
21000	.98	1.18	1.30	1.60	1.72	2.05	2.24	3.67	5.60	15.97	23.68	37.94	37.93	29.65	25.79
22000	1.05	1.21	1.32	1.65	1.80	2.16	2.35	3.15	4.33	11.90	18.18	34.82	37.53	32.38	28.76
23000	1.13	1.28	1.37	1.68	1.86	2.26	2.46	3.09	3.73	9.19	14.12	30.75	35.74	34.51	31.39
24000	1.21	1.36	1.44	1.72	1.90	2.36	2.57	3.19	3.60	7.36	11.25	26.50	32.96	35.97	33.63
25000	1.30	1.45	1.53	1.79	1.95	2.45	2.68	3.31	3.68	6.16	9.21	22.61	29.70	36.71	35.40
26000	1.39	1.55	1.63	1.87	2.02	2.52	2.78	3.44	3.81	5.52	7.78	19.31	26.41	36.75	36.68
27000	1.49	1.65	1.74	1.98	2.12	2.58	2.86	3.58	3.95	5.31	6.88	16.64	23.37	36.18	37.45
28000	1.59	1.76	1.84	2.09	2.23	2.67	2.94	3.71	4.09	5.34	6.44	14.53	20.73	35.14	37.76
29000	1.69	1.87	1.96	2.21	2.35	2.77	3.03	3.84	4.24	5.47	6.34	12.87	18.52	33.77	37.64
30000	1.79	1.98	2.07	2.34	2.47	2.89	3.14	3.96	4.39	5.62	6.41	11.61	16.69	32.23	37.19

TABLE IV.- TRANSPORT PROPERTIES FOR NITROGEN - Concluded
(c) Prandtl number, Pr

T, °K	Pressure, Atmospheres														
	0.0001	0.0005	0.001	0.005	0.01	0.05	0.1	0.5	1	5	10	50	100	500	1,000
293	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369	.7369
500	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397	.7397
1000	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580	.7580
1500	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692	.7692
2000	.7744	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745	.7745
2500	.7759	.7766	.7768	.7769	.7770	.7771	.7771	.7772	.7772	.7772	.7772	.7772	.7772	.7772	.7772
3000	.7405	.7601	.7653	.7725	.7743	.7768	.7774	.7781	.7783	.7786	.7786	.7787	.7787	.7788	.7788
3500	.6048	.6525	.6744	.7188	.7335	.7568	.7631	.7720	.7742	.7773	.7780	.7790	.7792	.7795	.7796
3750	.5690	.5940	.6117	.6617	.6834	.7258	.7392	.7601	.7656	.7734	.7754	.7780	.7786	.7794	.7796
4000	.5763	.5675	.5738	.6071	.6275	.6792	.6996	.7371	.7482	.7650	.7693	.7753	.7768	.7788	.7793
4250	.6335	.5770	.5682	.5740	.5859	.6293	.6519	.7020	.7198	.7496	.7579	.7700	.7730	.7772	.7782
4500	.7521	.6279	.5977	.5673	.5674	.5906	.6086	.6600	.6824	.7257	.7394	.7606	.7662	.7741	.7761
4750	.9035	.7284	.6695	.5889	.5736	.5700	.5794	.6201	.6425	.6945	.7136	.7462	.7554	.7690	.7724
5000	.9998	.8640	.7849	.6431	.6071	.5690	.5675	.5897	.6078	.6599	.6826	.7262	.7399	.7611	.7667
5250	.9881	.9751	.9130	.7334	.6721	.5888	.5736	.5722	.5831	.6269	.6501	.7016	.7197	.7500	.7584
5500	.8746	1.0062	.9953	.8478	.7679	.6318	.5991	.5685	.5703	.5998	.6204	.6742	.6959	.7354	.7473
5750	.7022	.9453	.9965	.9504	.8773	.7000	.6461	.5792	.5700	.5810	.5965	.6468	.6703	.7178	.7333
6000	.5452	.8107	.9150	1.0018	.9657	.7894	.7153	.6053	.5827	.5713	.5800	.6218	.6450	.6978	.7167
6250	.4547	.6465	.7730	.9844	1.0023	.8845	.8016	.6479	.6091	.5711	.5717	.6011	.6220	.6764	.6981
6500	.4085	.5179	.6170	.9005	.9754	.9607	.8903	.7072	.6504	.5807	.5718	.5857	.6027	.6551	.6785
6750	.3823	.4453	.5035	.7686	.8888	.9965	.9603	.7798	.7061	.6005	.5805	.5762	.5881	.6350	.6589
7000	.3659	.4061	.4395	.6267	.7603	.9821	.9938	.8572	.7735	.6310	.5982	.5728	.5784	.6171	.6401
7250	.3545	.3827	.4039	.5183	.6253	.9178	.9821	.9260	.8457	.6724	.6252	.5756	.5741	.6020	.6230
7500	.3454	.3674	.3821	.4526	.5215	.8136	.9248	.9728	.9120	.7236	.6615	.5848	.5751	.5902	.6083
7750	.3361	.3565	.3676	.4143	.4567	.6912	.8299	.9879	.9609	.7821	.7067	.6005	.5816	.5821	.5962
8000	.3240	.3476	.3569	.3907	.4181	.5807	.7150	.9670	.9834	.8427	.7590	.6228	.5937	.5775	.5871
8250	.3059	.3390	.3482	.3749	.3941	.5006	.6057	.9113	.9745	.8987	.8148	.6518	.6114	.5768	.5811
8500	.2787	.3289	.3399	.3634	.3778	.4490	.5215	.8271	.9336	.9429	.8693	.6870	.6349	.5799	.5783
8750	.2411	.3152	.3303	.3543	.3660	.4164	.4646	.7275	.8645	.9689	.9165	.7277	.6639	.5869	.5787
9000	.1960	.2957	.3179	.3464	.3568	.3949	.4278	.6299	.7759	.9724	.9508	.7721	.6979	.5978	.5824
9250	.1498	.2689	.3006	.3385	.3489	.3798	.4035	.5490	.6814	.9517	.9675	.8180	.7362	.6125	.5893
9500	.1093	.2346	.2772	.3294	.3413	.3686	.3866	.4895	.5953	.9078	.9639	.8621	.7772	.6311	.5995
9750	.0779	.1956	.2471	.3182	.3331	.3596	.3742	.4482	.5266	.8442	.9391	.9010	.8190	.6534	.6130
10000	.0557	.1560	.2119	.3035	.3234	.3520	.3646	.4198	.4762	.7676	.8943	.9312	.8589	.7611	.6297
10500	.0314	.0910	.1393	.2609	.2956	.3378	.3495	.3853	.4156	.6121	.7616	.9542	.9224	.7393	.6723
11000	.0218	.0525	.0837	.2024	.2526	.3209	.3359	.3654	.3840	.4982	.6168	.9184	.9475	.8050	.7250
11500	.0188	.0335	.0510	.1417	.1973	.2967	.3194	.3514	.3652	.4323	.5068	.8283	.9226	.8663	.7835
12000	.0187	.0249	.0342	.0936	.1416	.2621	.2965	.3392	.3518	.3956	.4395	.7080	.8493	.9111	.8407
12500	.0197	.0216	.0263	.0621	.0970	.2182	.2649	.3261	.3402	.3738	.4008	.5913	.7437	.9286	.8874
13000	.0212	.0207	.0229	.0436	.0667	.1712	.2254	.3097	.3281	.3592	.3774	.5014	.6317	.9124	.9149
13500	.0244	.0209	.0217	.0335	.0480	.1285	.1824	.2683	.3137	.3480	.3620	.4415	.5365	.8626	.9164
14000	.0314	.0219	.0216	.0281	.0371	.0948	.1418	.2611	.2955	.3381	.3506	.4035	.4671	.7862	.8893
14500	.0457	.0248	.0224	.0254	.0310	.0707	.1080	.2291	.2727	.3280	.3410	.3793	.4206	.6959	.8356
15000	.0724	.0316	.0253	.0240	.0275	.0545	.0824	.1947	.2454	.3167	.3319	.3631	.3902	.6063	.7623
16000	.1616	.0655	.0443	.0246	.0245	.0371	.0517	.1312	.1842	.2873	.3115	.3422	.3558	.4674	.5985
17000	.1902	.1347	.0926	.0371	.0280	.0296	.0374	.0864	.1285	.2470	.2840	.3269	.3369	.3897	.4682
18000	.1132	.1767	.1552	.0695	.0465	.0269	.0303	.0598	.0886	.1999	.2480	.3114	.3230	.3499	.3893
19000	.0653	.1332	.1608	.1193	.0834	.0341	.0285	.0447	.0635	.1541	.2063	.2926	.3092	.3281	.3458
20000	.0185	.0684	.1062	.1501	.1269	.0554	.0376	.0357	.0482	.1162	.1649	.2691	.2933	.3139	.3211
21000	.0089	.0304	.0534	.1304	.1423	.0877	.0596	.0318	.0364	.0880	.1289	.2411	.2739	.3027	.3055
22000	.0055	.0143	.0250	.0844	.1165	.1177	.0891	.0373	.0337	.0680	.1004	.2103	.2509	.2920	.2939
23000	.0043	.0080	.0127	.0462	.0752	.1254	.1136	.0534	.0377	.0537	.0789	.1793	.2252	.2805	.2839
24000	.0038	.0055	.0076	.0243	.0426	.1067	.1183	.0751	.0513	.0437	.0628	.1503	.1982	.2677	.2741
25000	.0036	.0044	.0054	.0136	.0235	.0762	.1017	.0949	.0702	.0388	.0508	.1248	.1716	.2531	.2637
26000	.0035	.0039	.0045	.0086	.0137	.0486	.0750	.1042	.0877	.0415	.0432	.1033	.1468	.2370	.2524
27000	.0035	.0037	.0040	.0062	.0089	.0297	.0501	.0994	.0974	.0512	.0414	.0854	.1246	.2196	.2400
28000	.0035	.0036	.0038	.0050	.0064	.0184	.0319	.0839	.0959	.0643	.0465	.0708	.1054	.2015	.2267
29000	.0035	.0036	.0037	.0043	.0052	.0121	.0204	.0643	.0846	.0763	.0563	.0593	.0889	.1831	.2125
30000	.0035	.0035	.0036	.0040	.0045	.0086	.0136	.0462	.0684	.0835	.0671	.0513	.0751	.1651	.1978
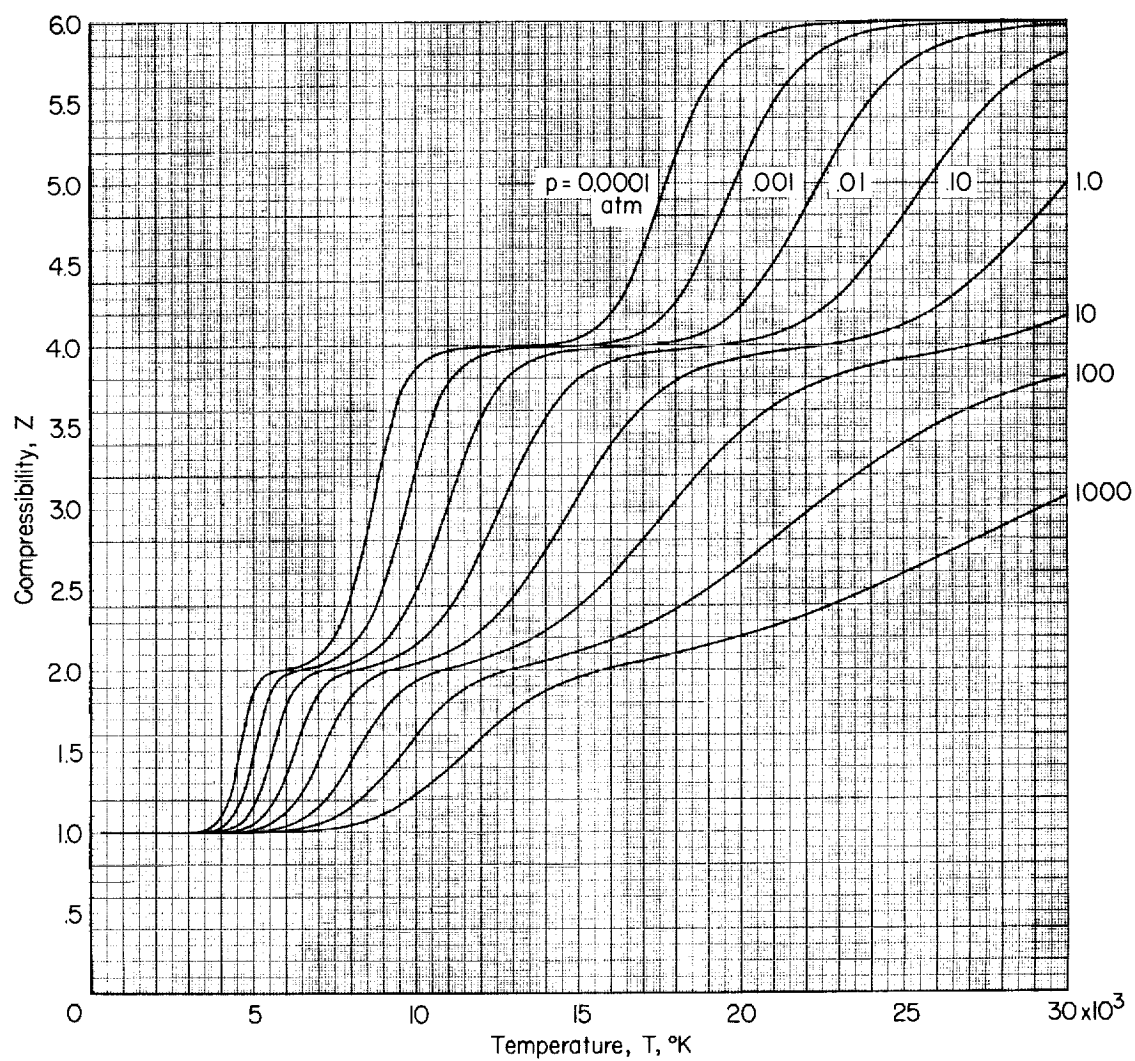
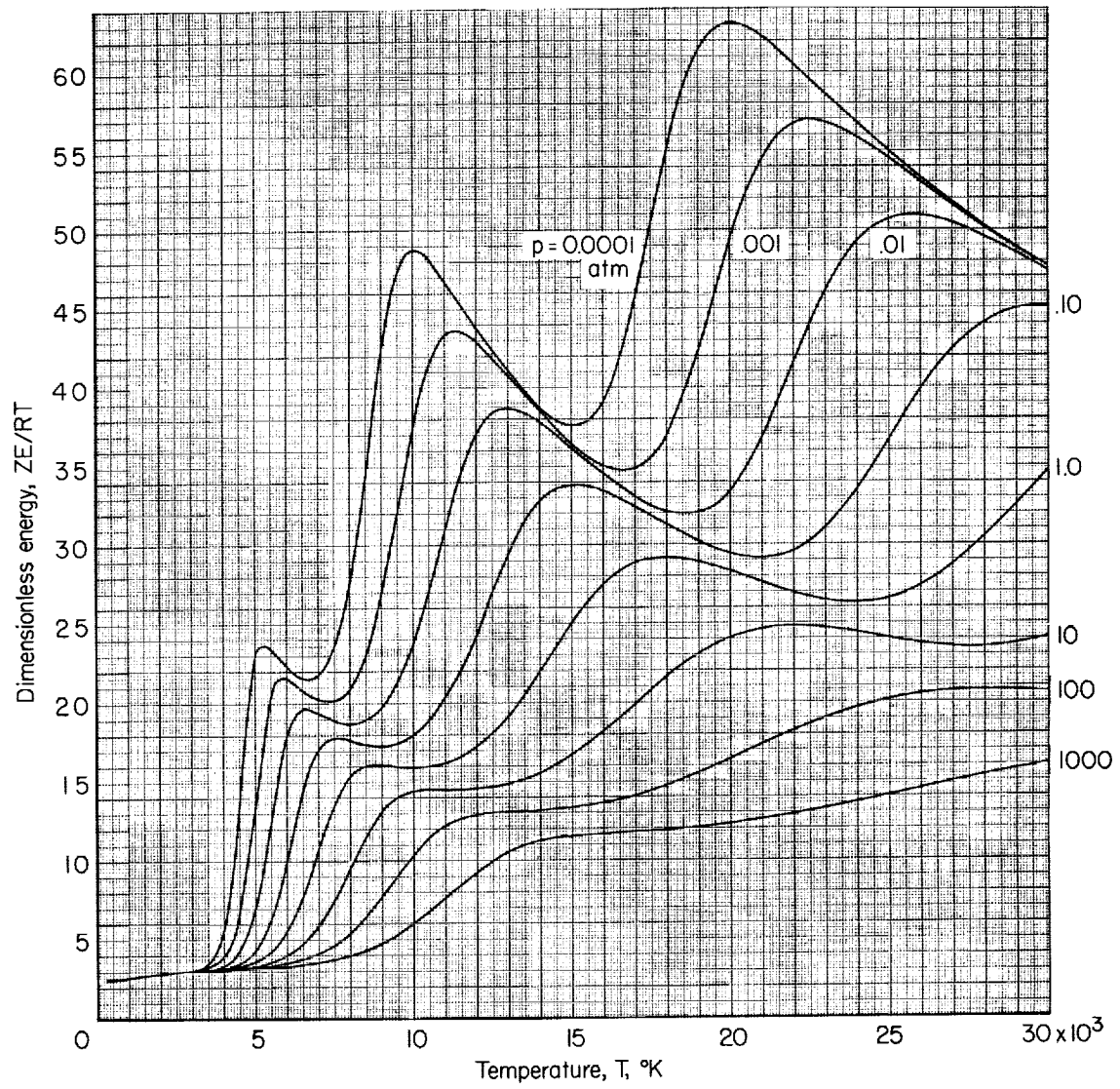Figure 1.- Compressibility of nitrogen as a function of temperature.

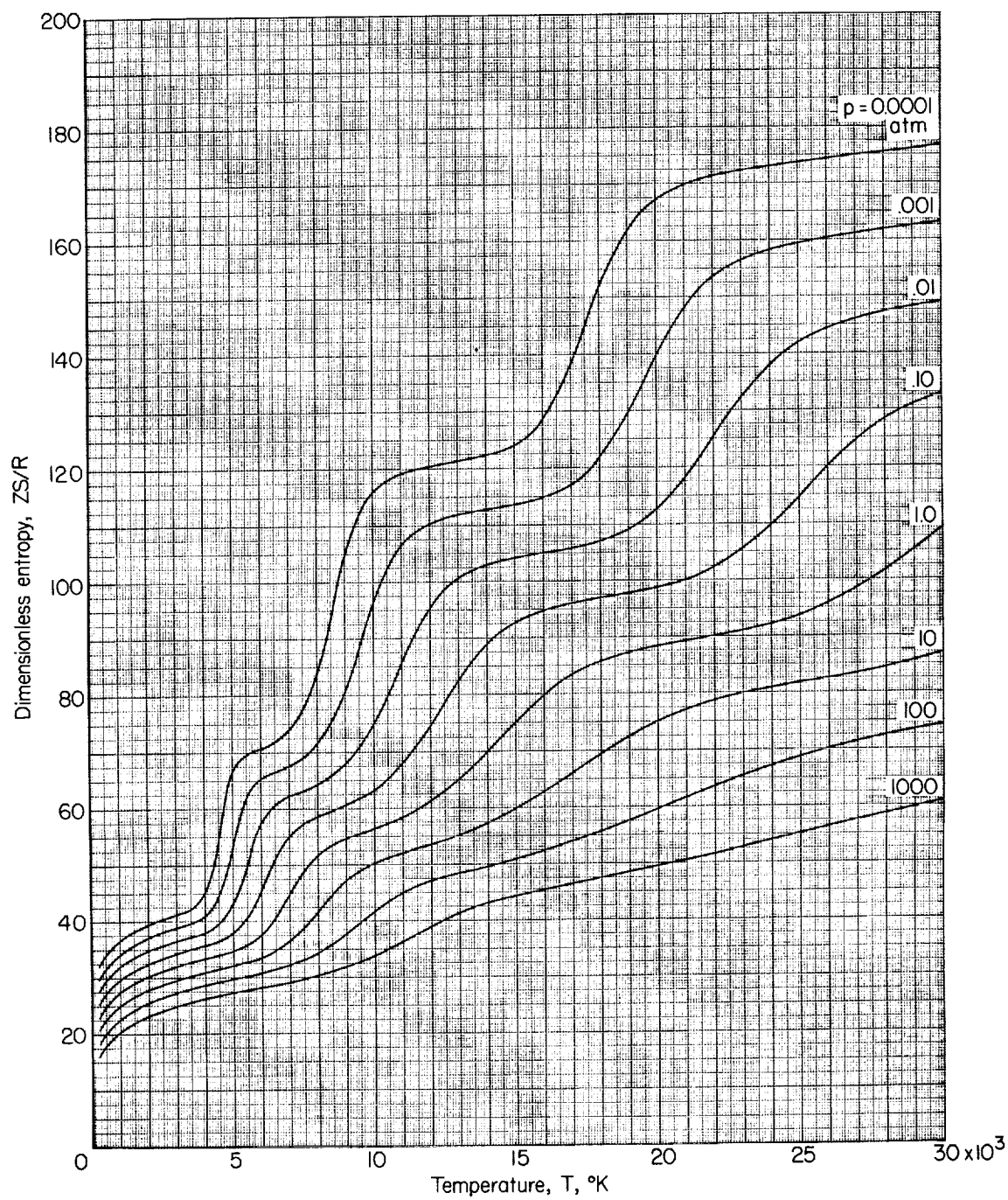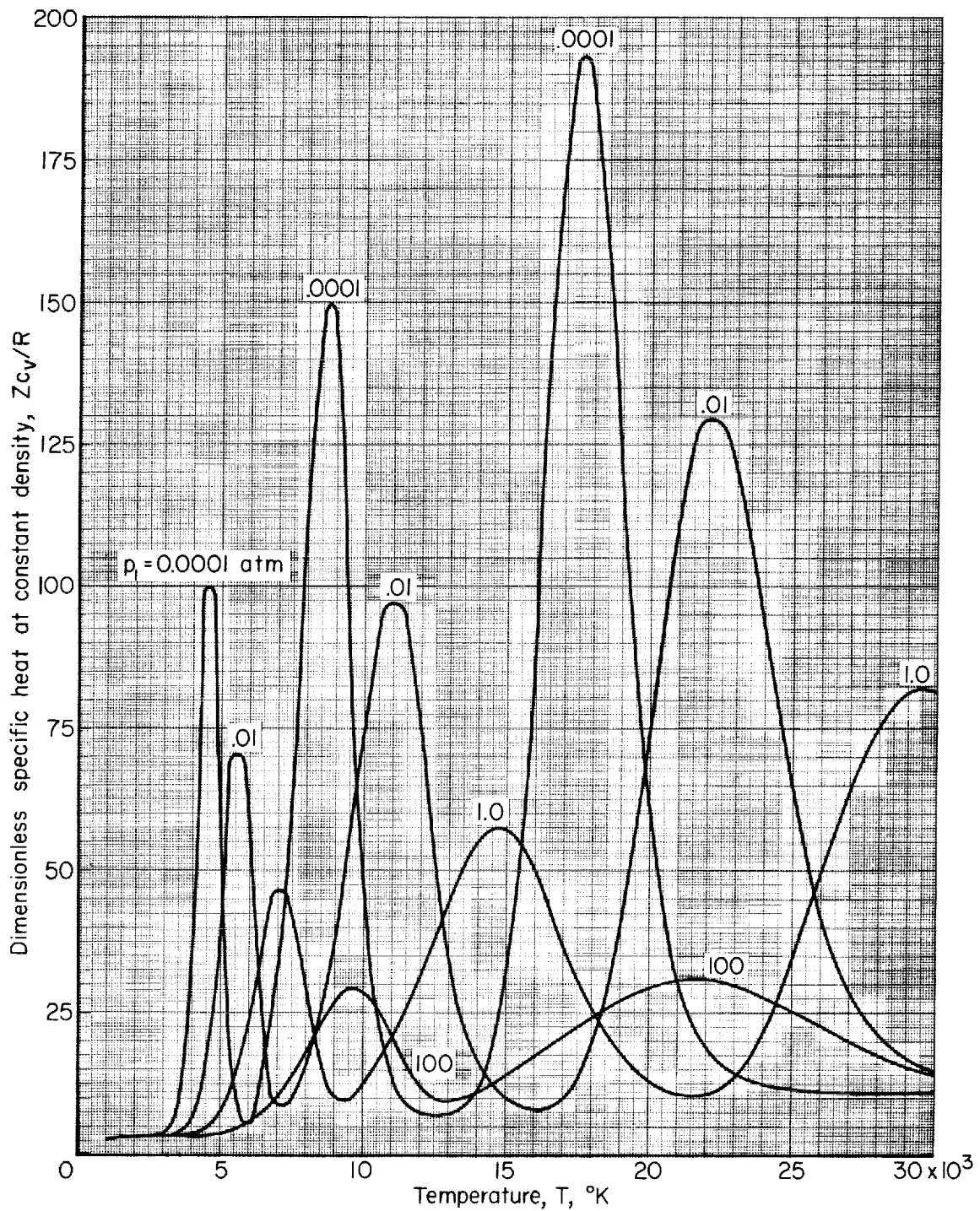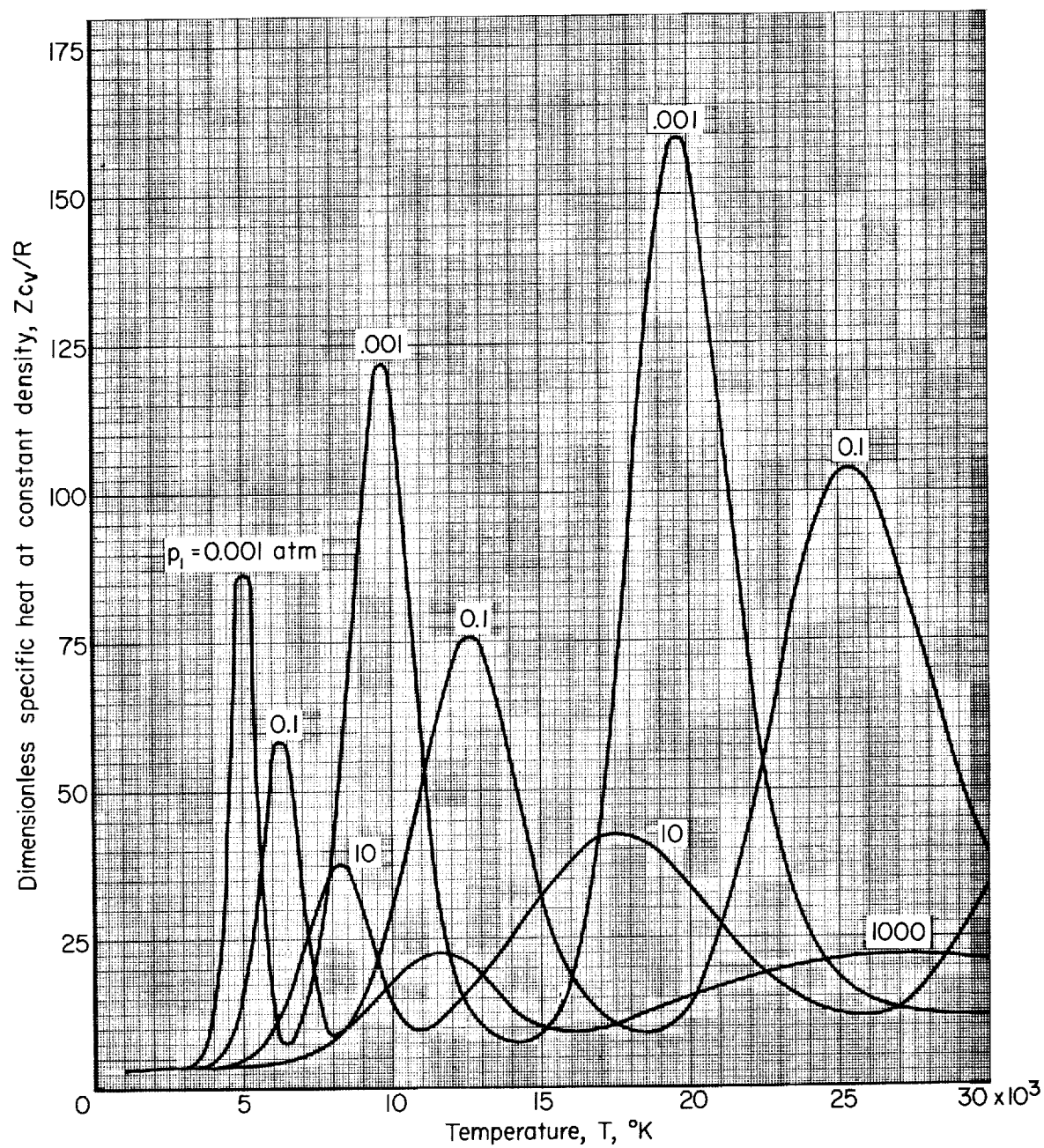Figure 2.- Energy of nitrogen as a function of temperature.

Figure 3.- Entropy of nitrogen as a function of temperature.
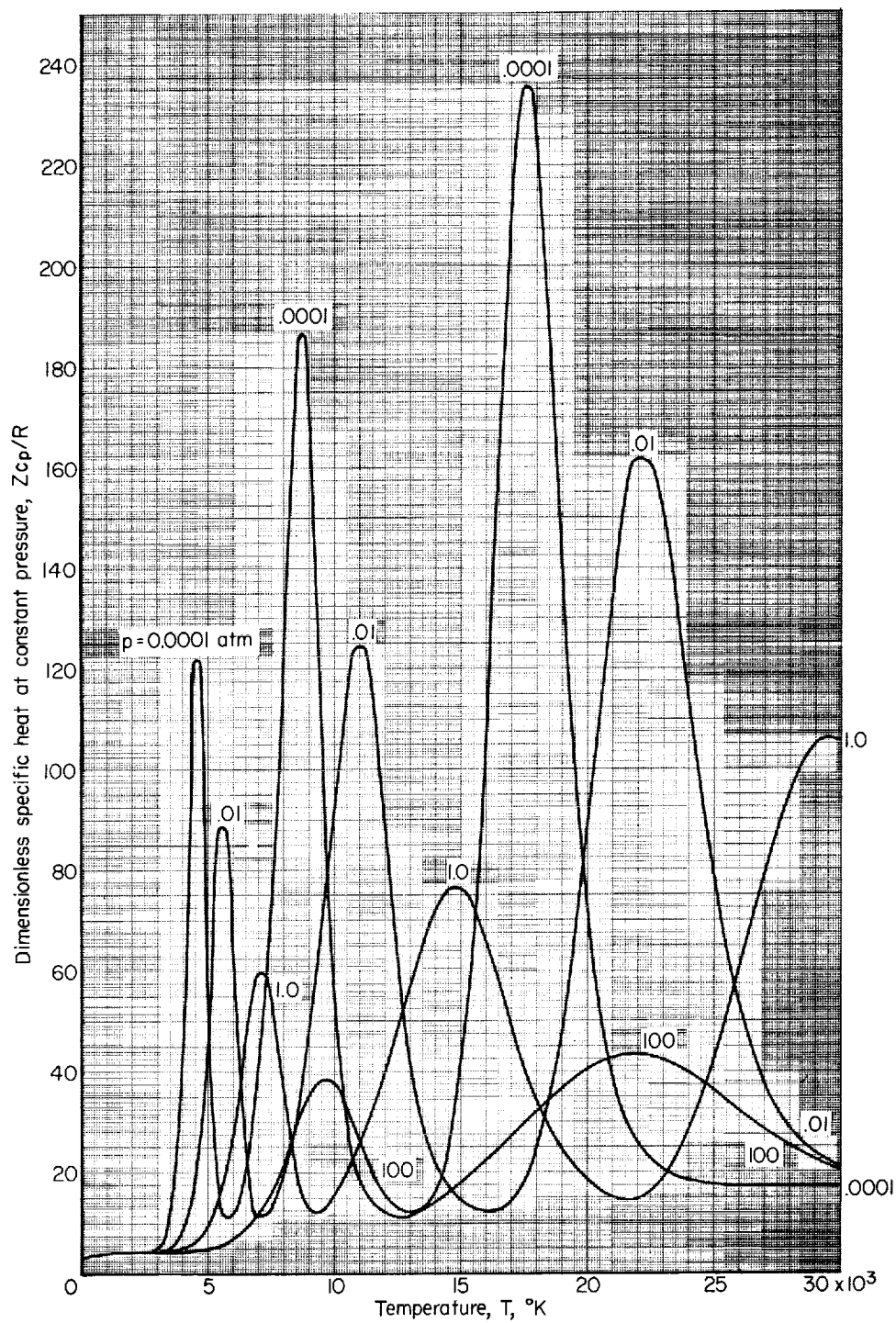
(a) Even powers of pressure.

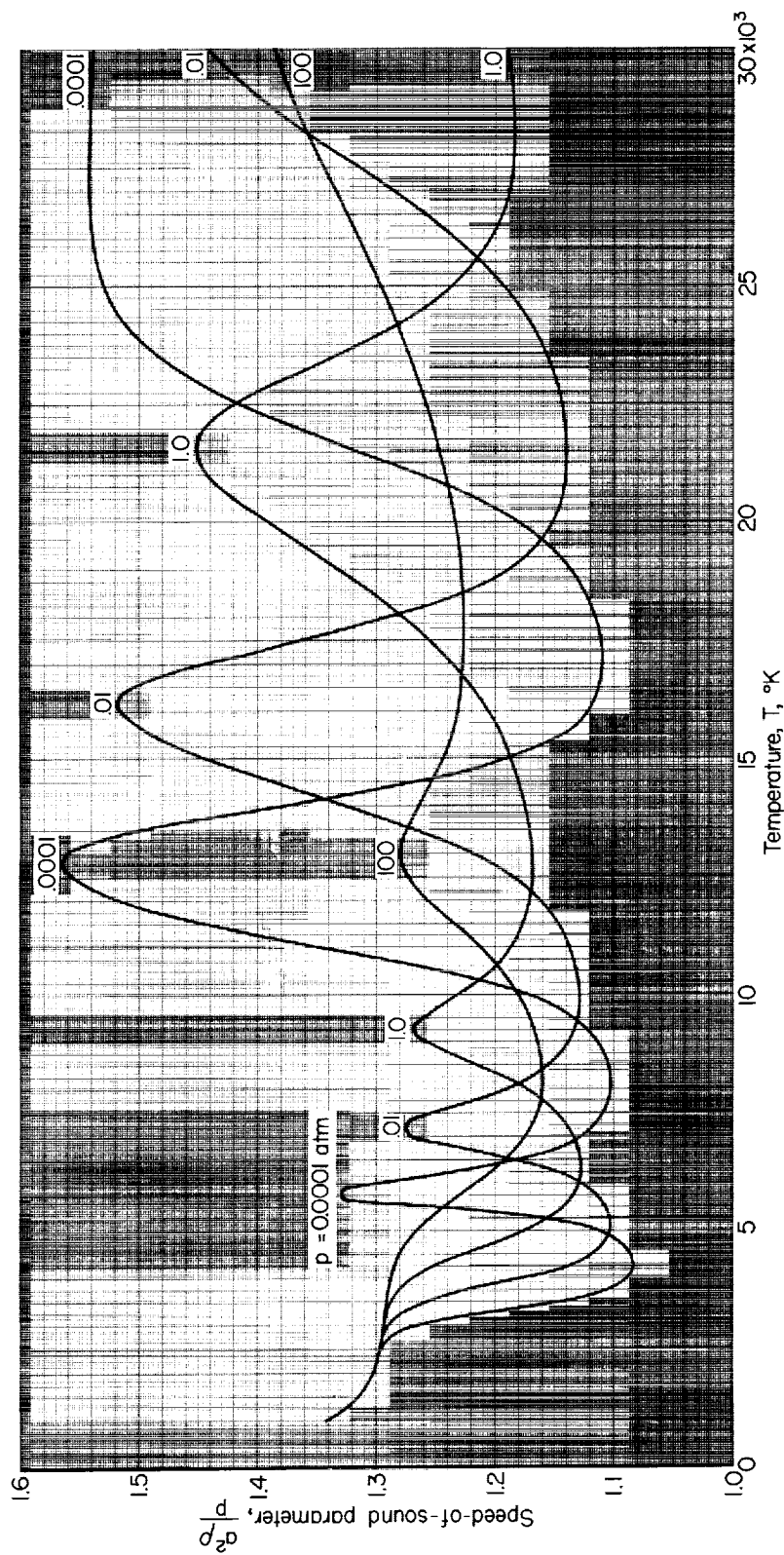Figure 4.- Specific heat of nitrogen at constant density as a function
of temperature.

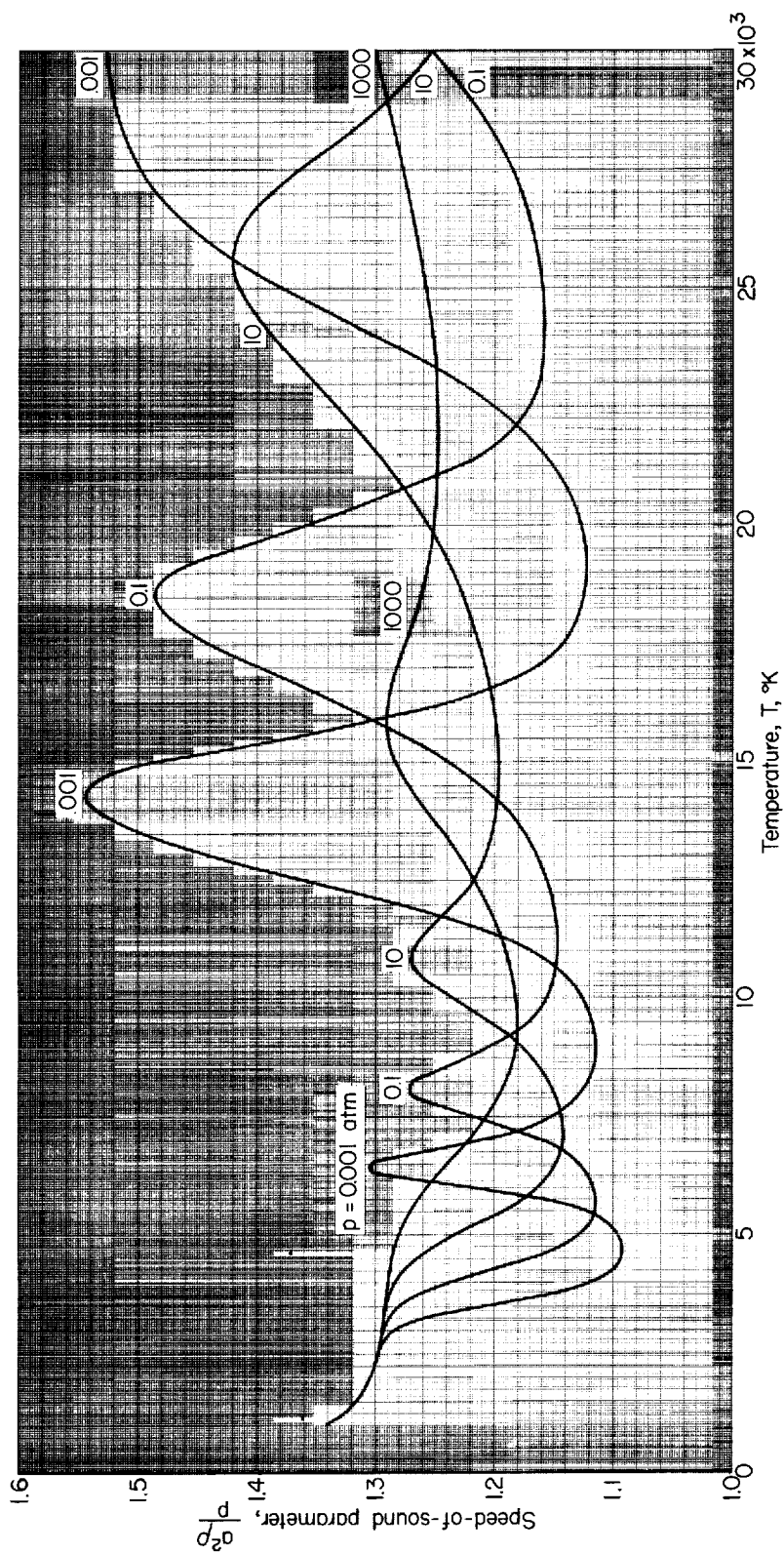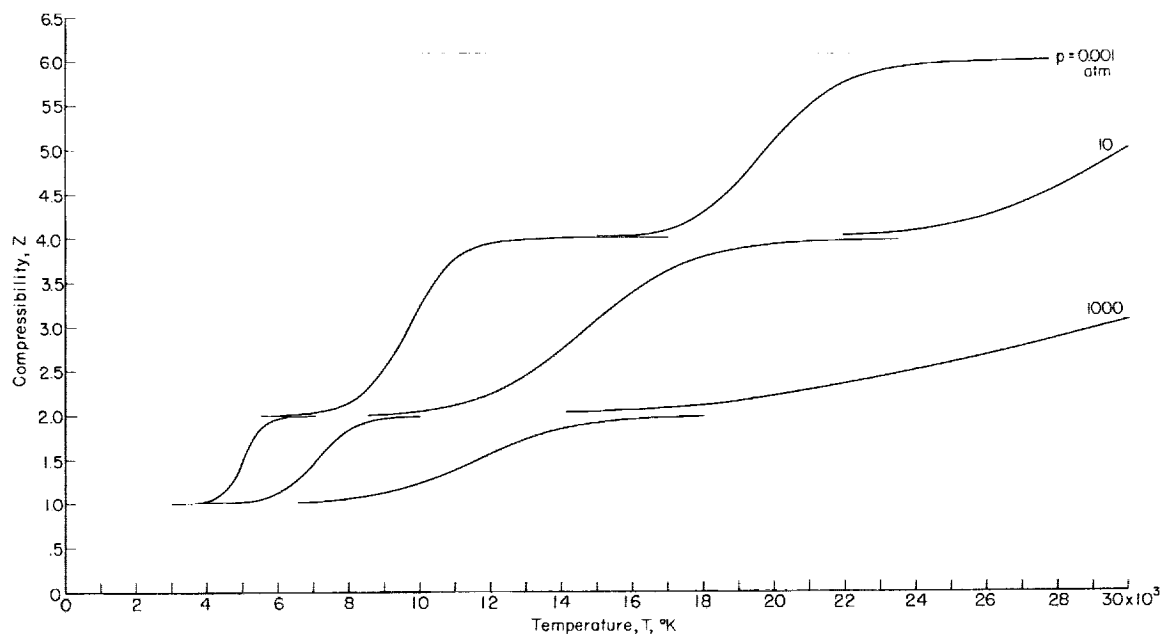(b) Odd powers of pressure.

Figure 4.- Concluded.

(a) Even powers of pressure.

Figure 5.- Specific heat of nitrogen at constant pressure as a function
of temperature

(b) Odd powers of pressure.

Figure 5.- Concluded.

(a) Even powers of pressure.

Figure 6.- Zero frequency speed-of-sound parameter for nitrogen as a function of temperature.

(b) Odd powers of pressure.

Figure 6.- Concluded.

(a) Compressibility.
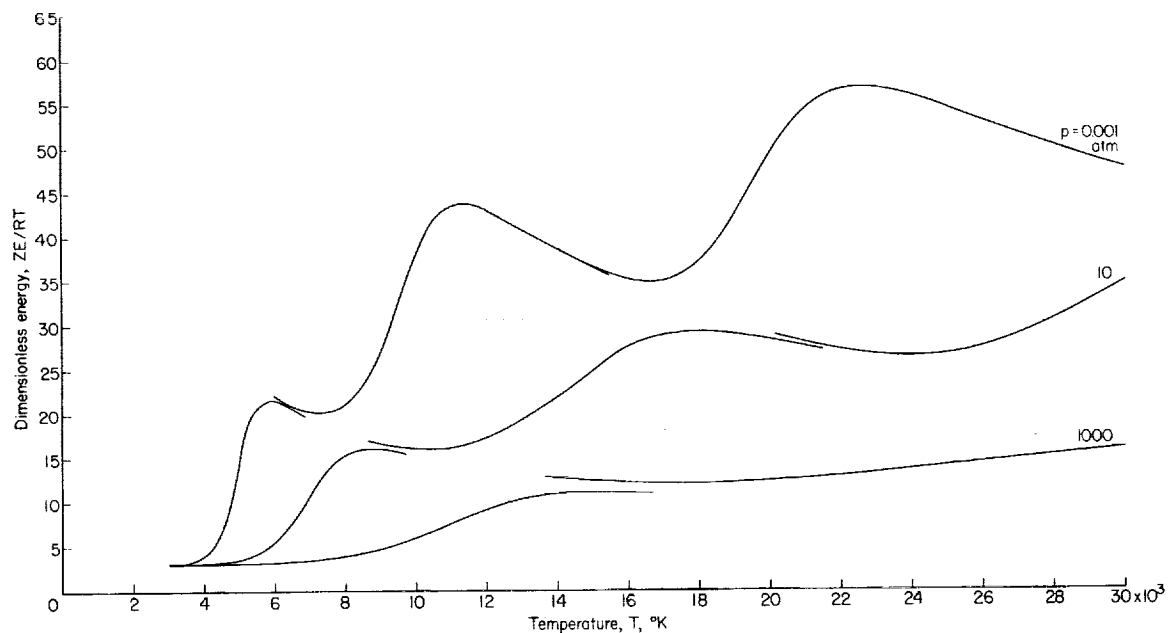
(b) Energy.

Figure 7.- Example of thermodynamic properties for independent nitrogen
reactions.
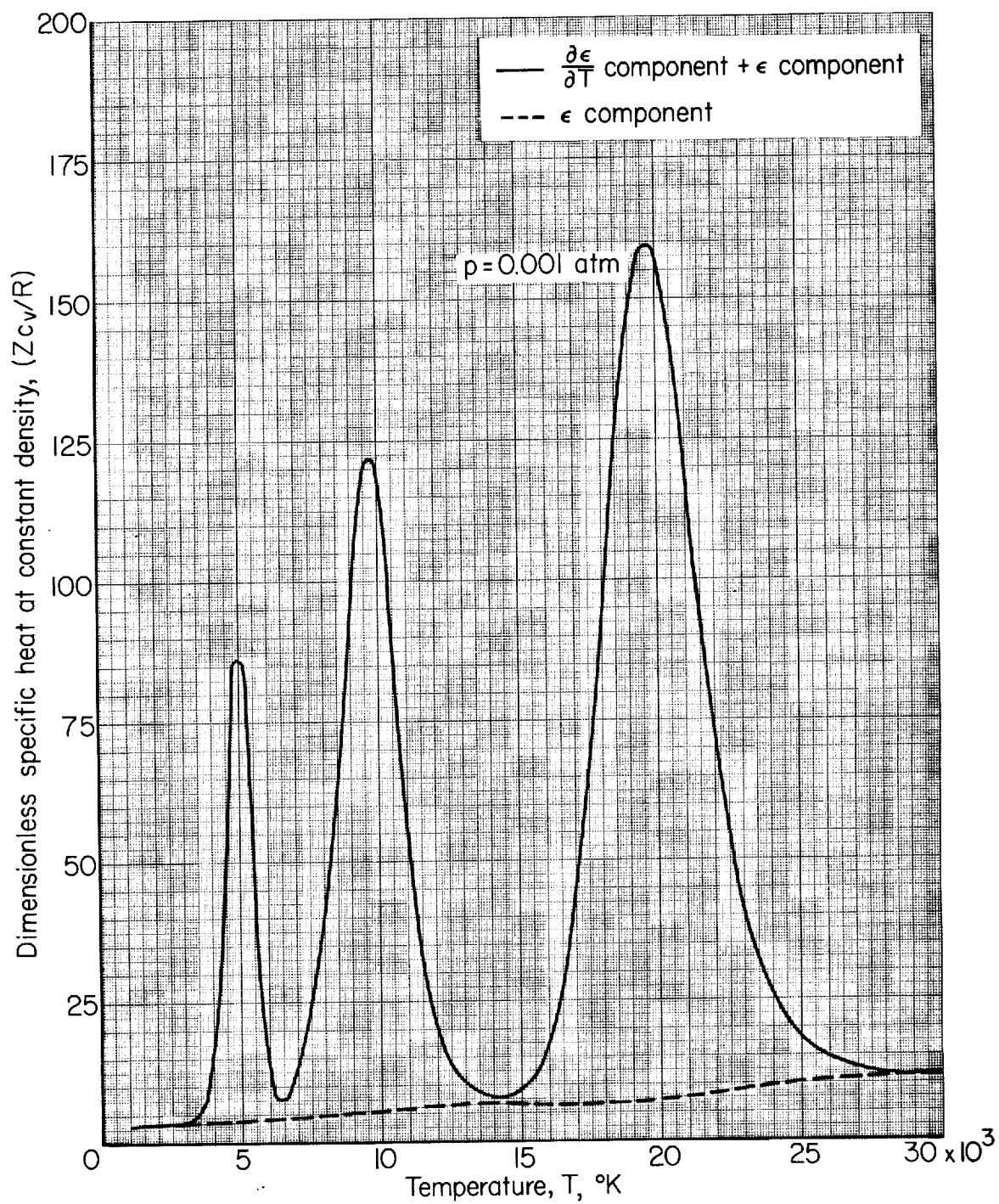
Figure 8.- Components of specific heat at constant density for nitrogen.
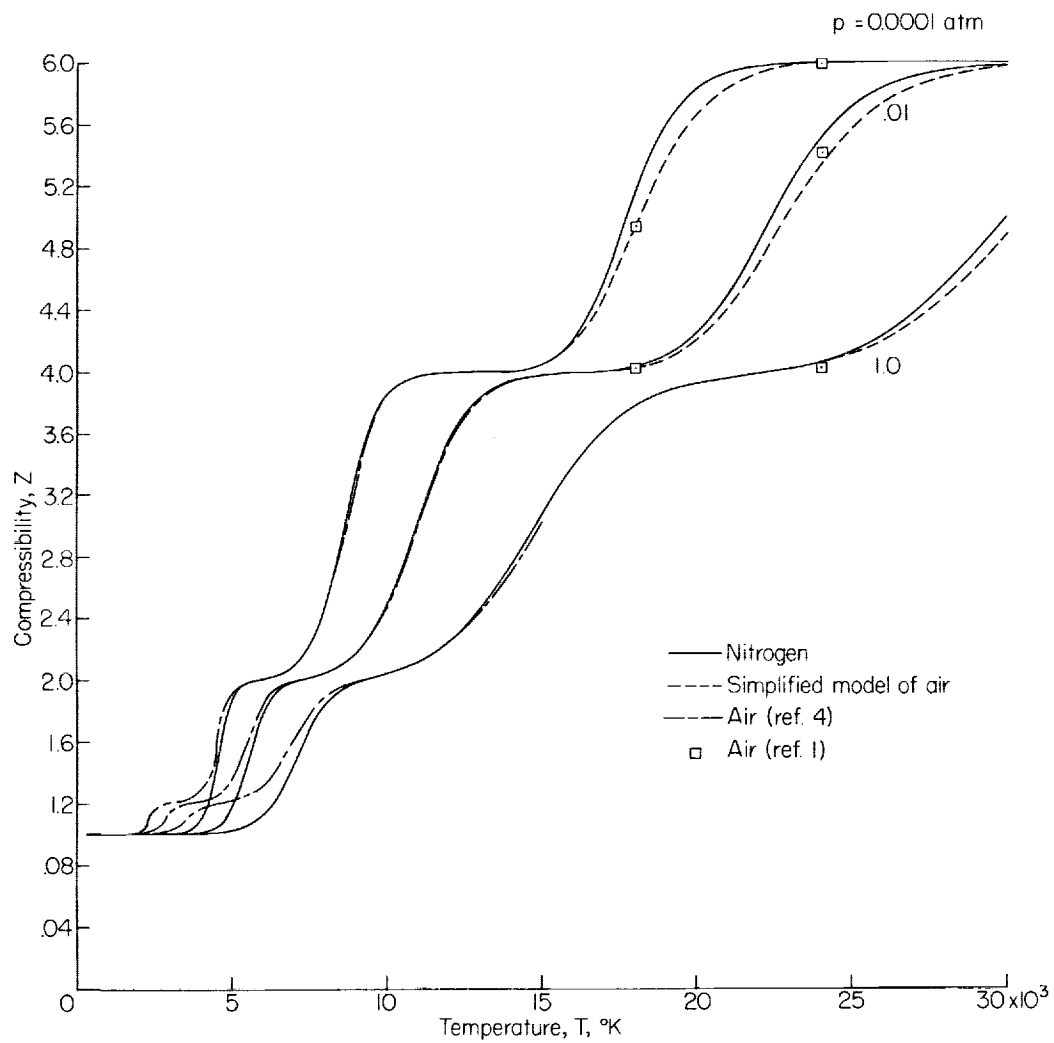
(a) Compressibility.

Figure 9.- Comparison of thermodynamic properties for air and nitrogen.
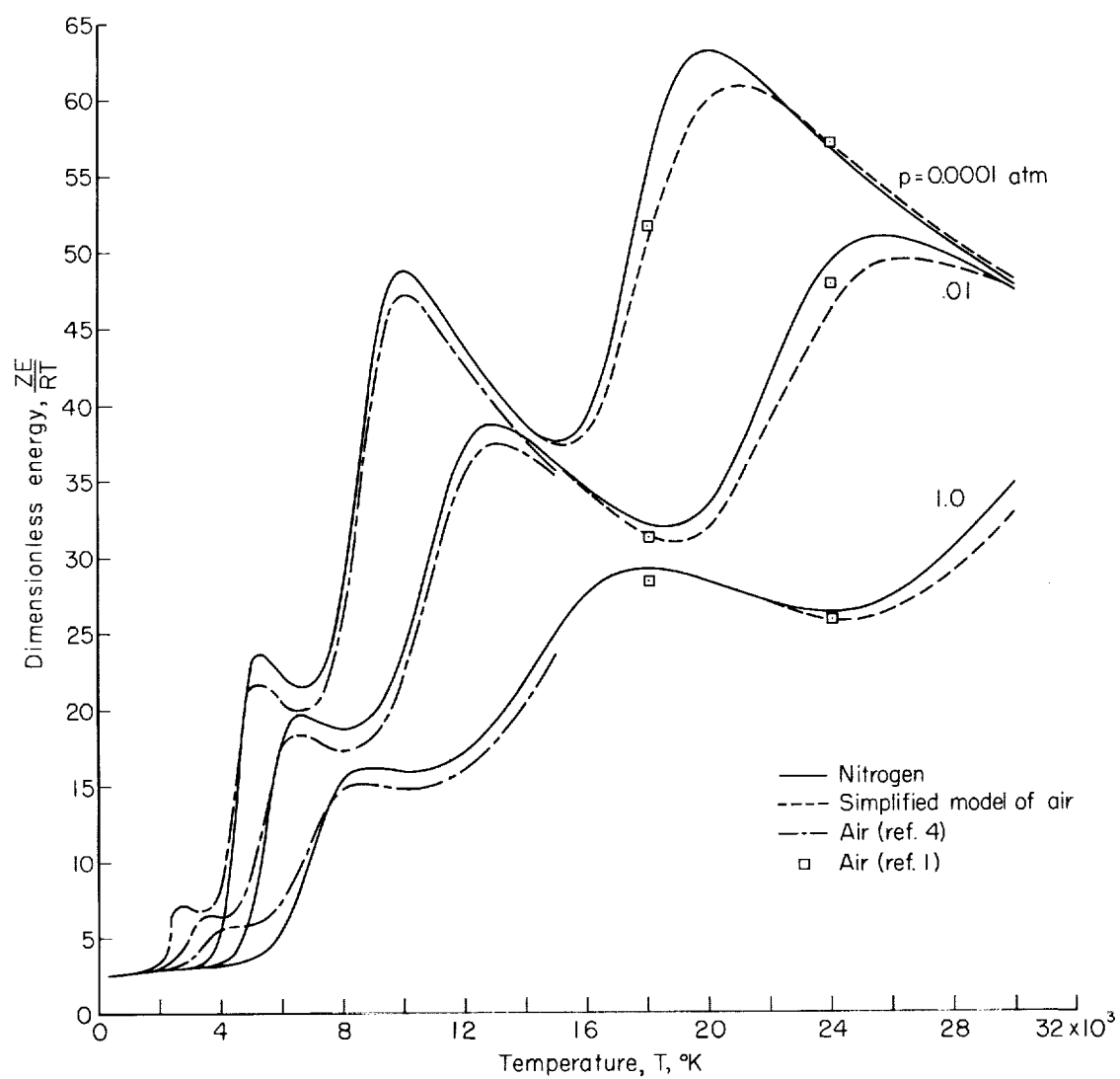
(b) Energy.

Figure 9.- Continued.
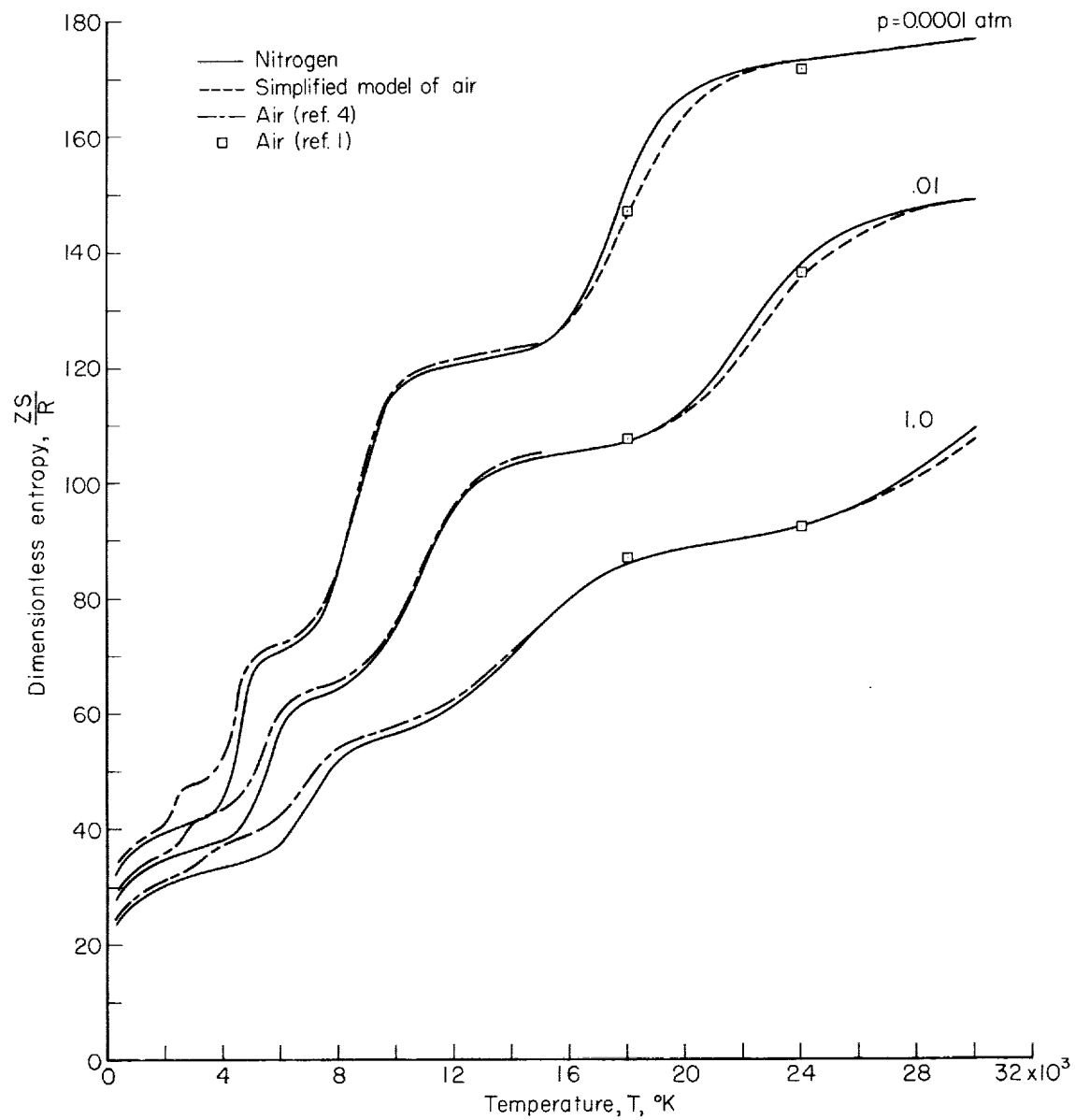
(c) Entropy.

Figure 9.- Continued.
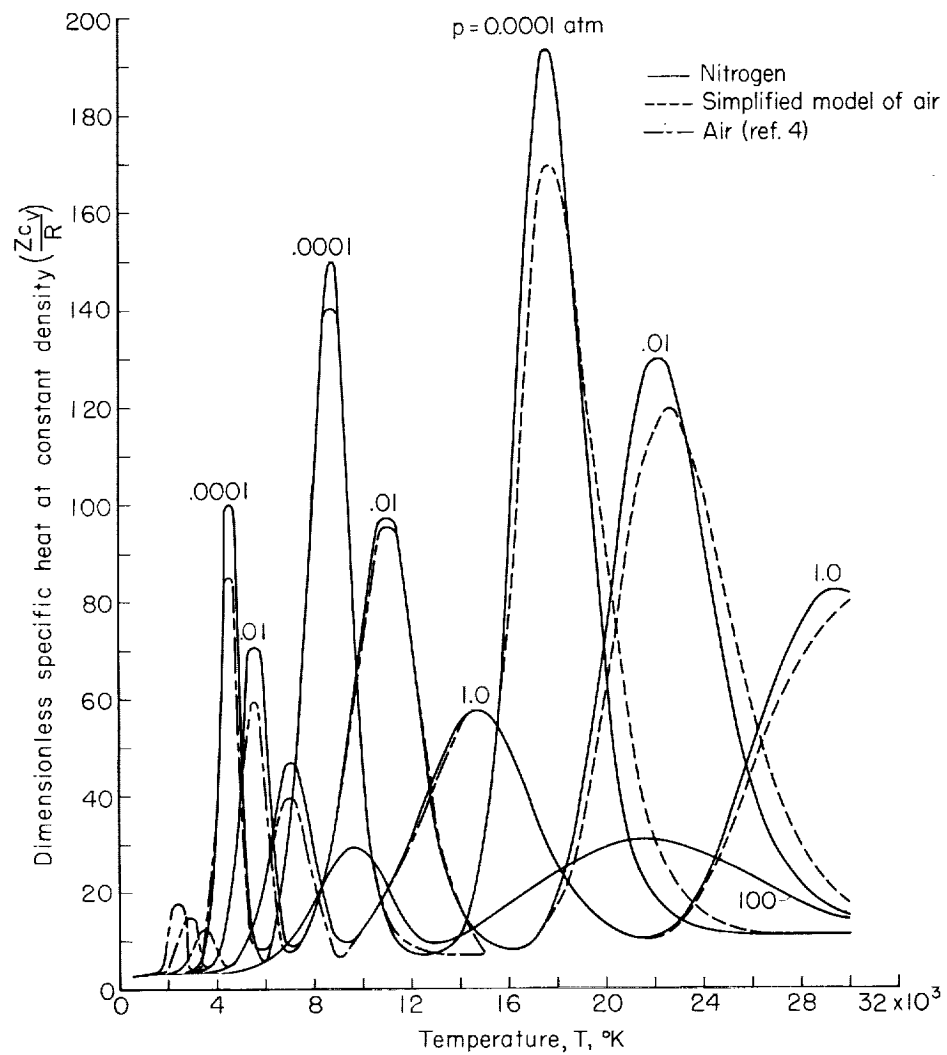
(d) Specific heat at constant density.

Figure 9.- Continued.

66

(e) Specific heat at constant pressure.

Figure 9.- Continued.
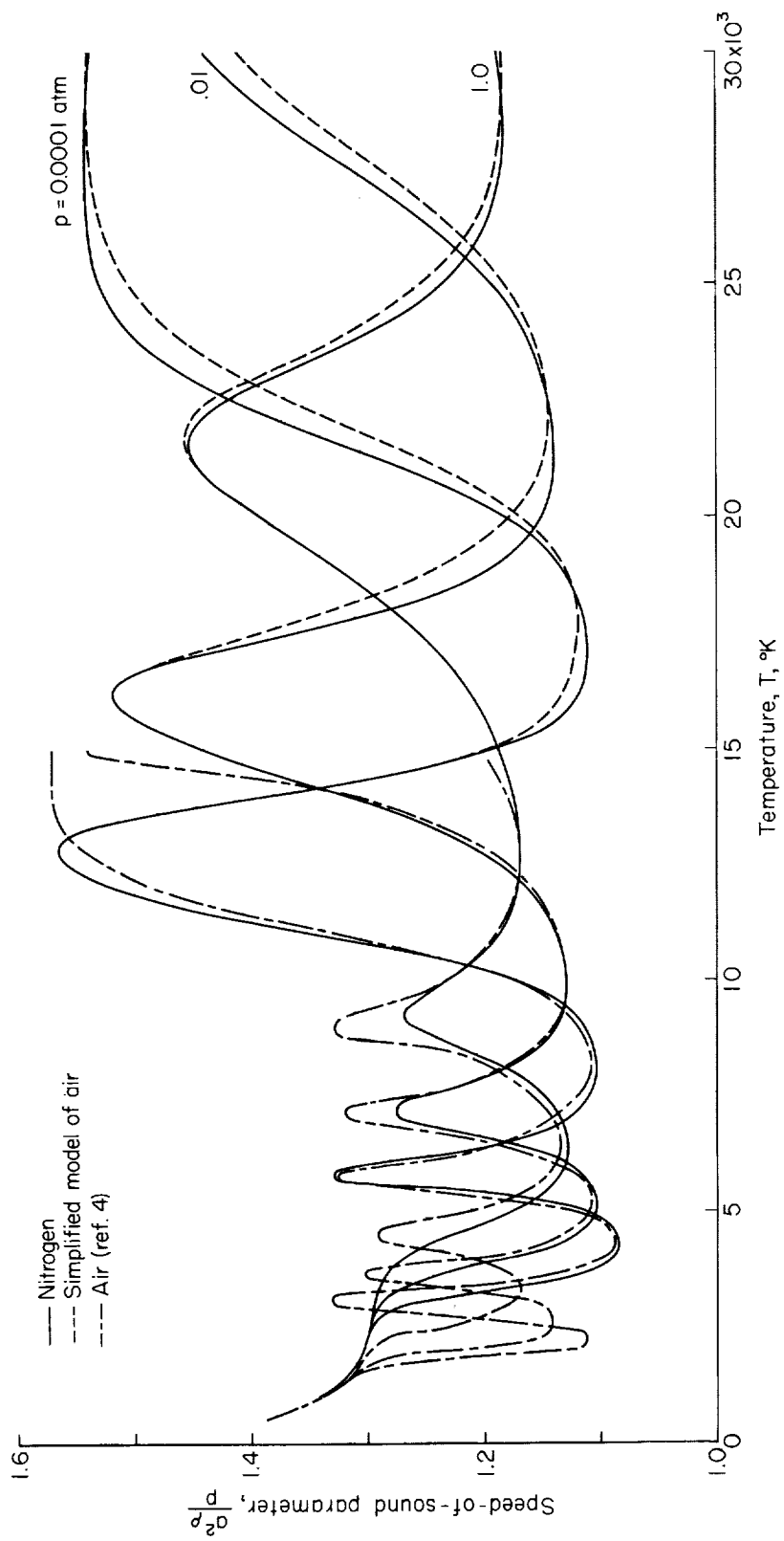
(f) Zero frequency speed-of-sound parameter.

Figure 9.- Concluded.
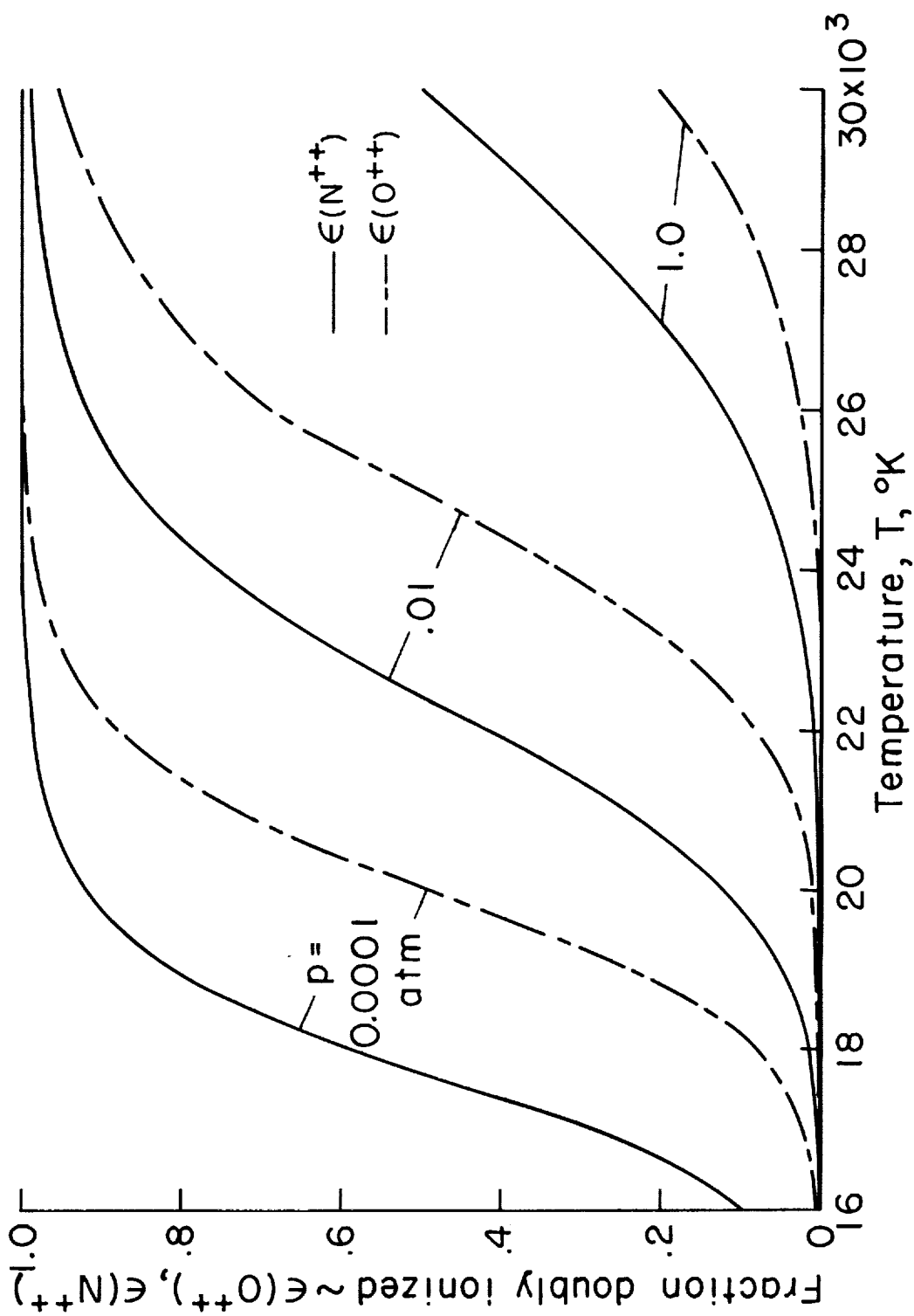
(a) Equilibrium fraction, ϵ.

Figure 10.- Comparison of ϵ and $\partial\epsilon/\partial T$ for oxygen and nitrogen.

(b) Derivative of the equilibrium fraction, $(\partial \epsilon / \partial T)_\rho$.
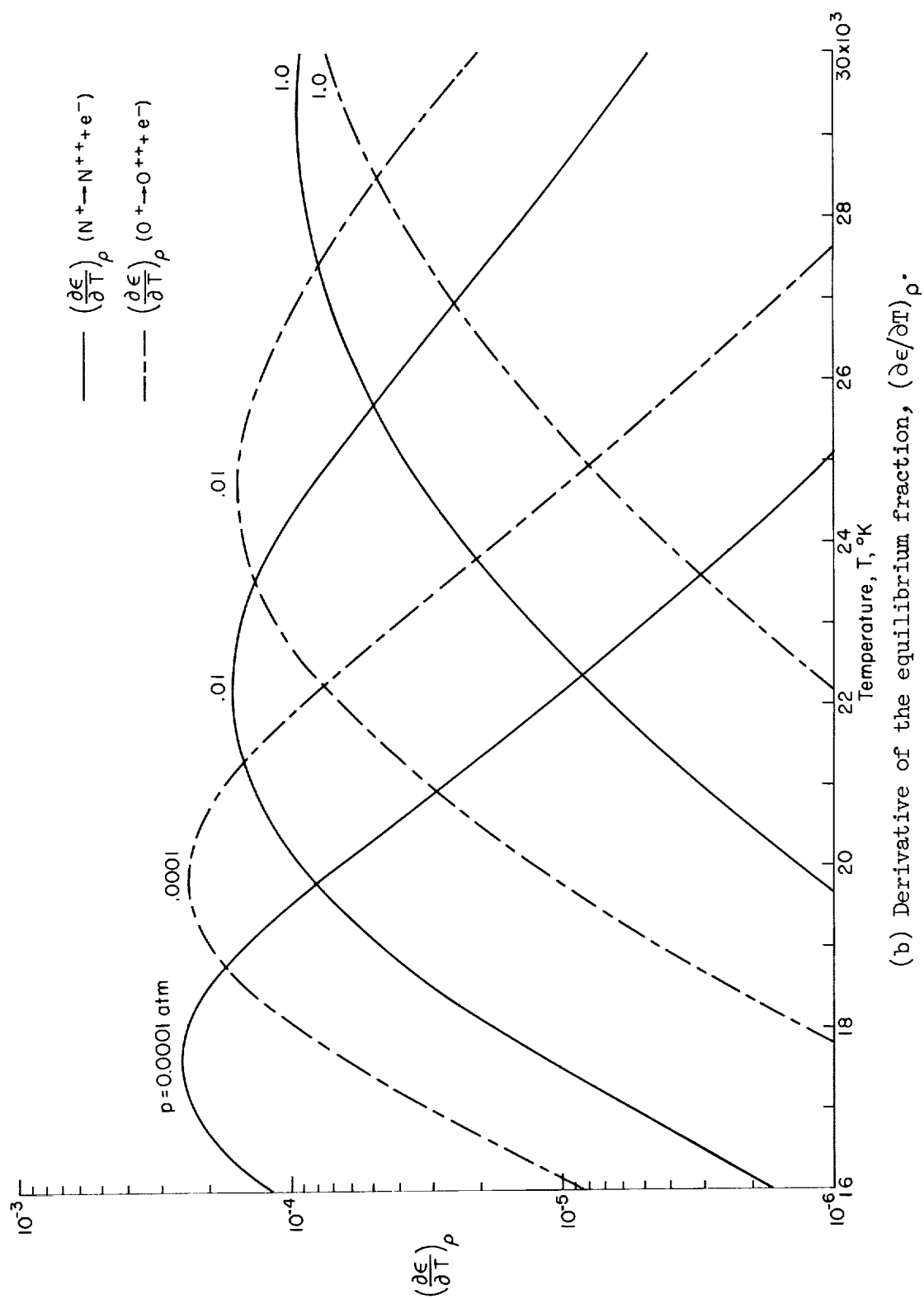
Figure 10.- Concluded.

70
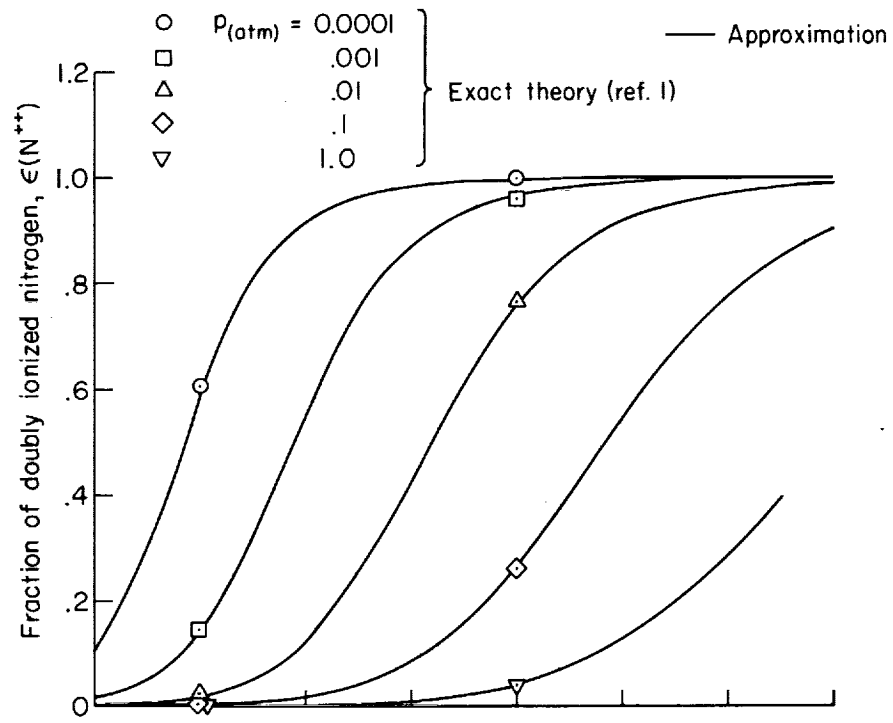
(a) Nitrogen component.
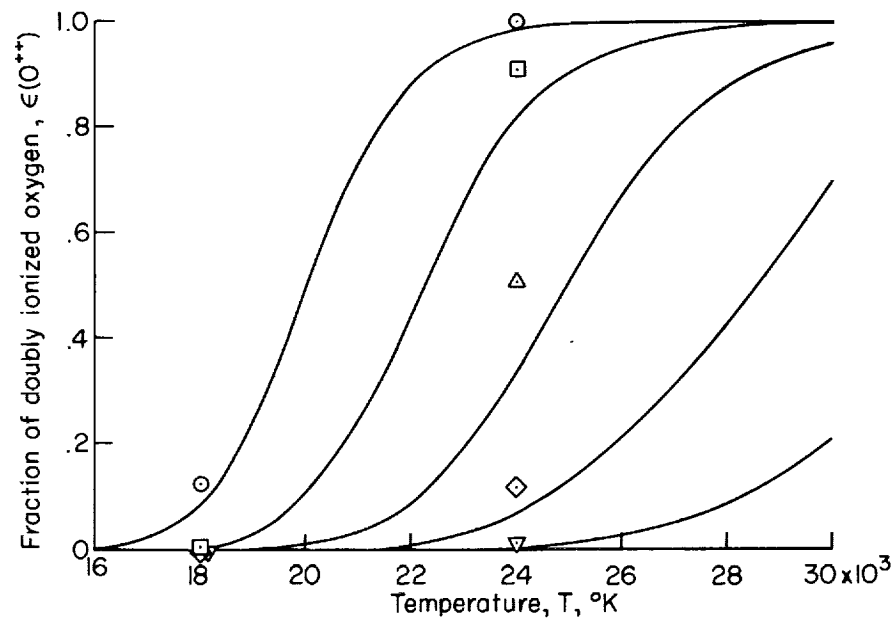
(b) Oxygen component.

Figure 11.- Comparison of fraction of doubly ionized atoms for exact and approximate models of air.
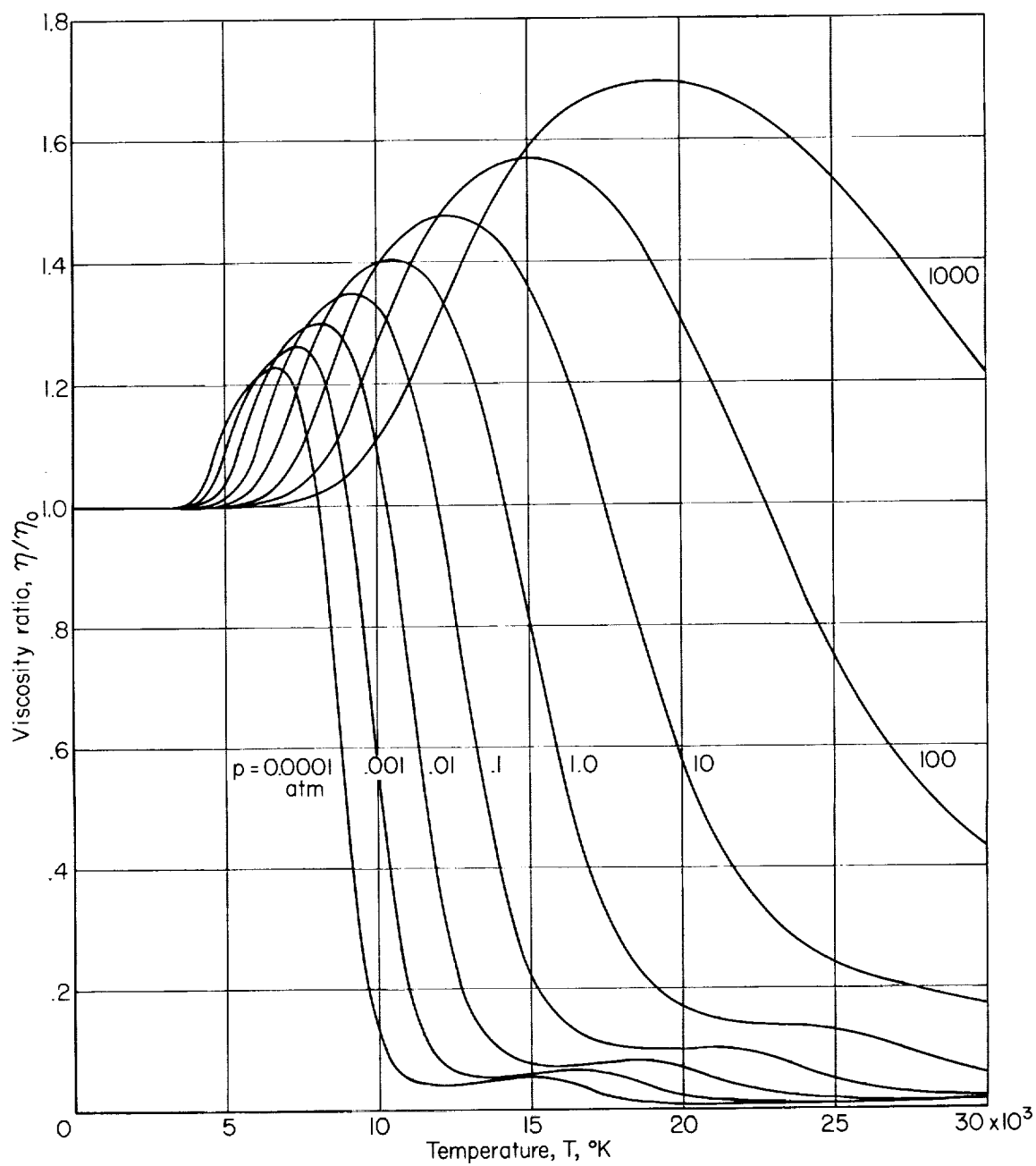
Figure 12.- Ratio of the coefficient of viscosity for nitrogen to the reference viscosity, η_0, as a function of temperature.

72
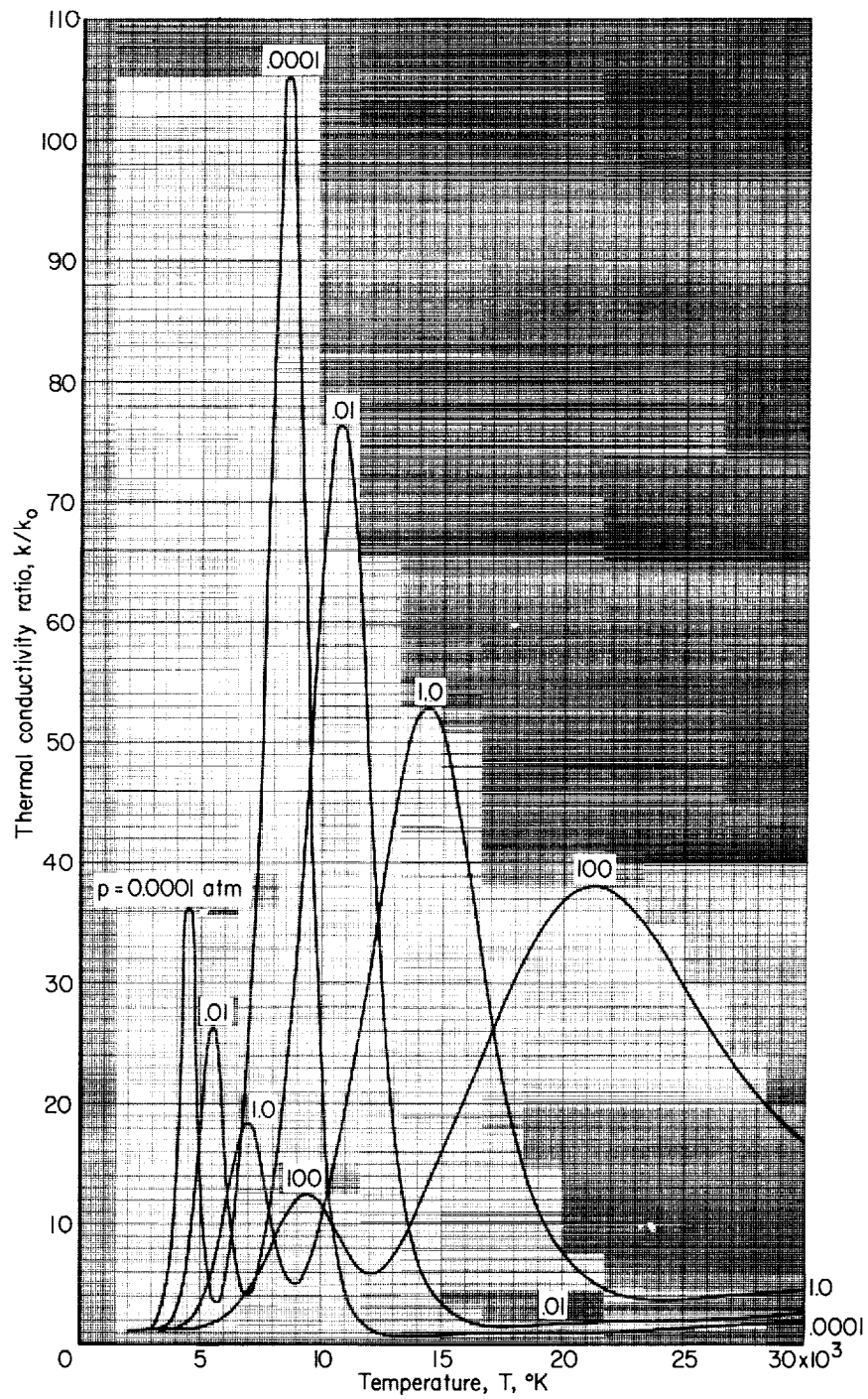
(a) Even powers of pressure.

Figure 13.- Ratio of the coefficient of thermal conductivity of nitrogen to the reference coefficient, k_O, as a function of temperature.
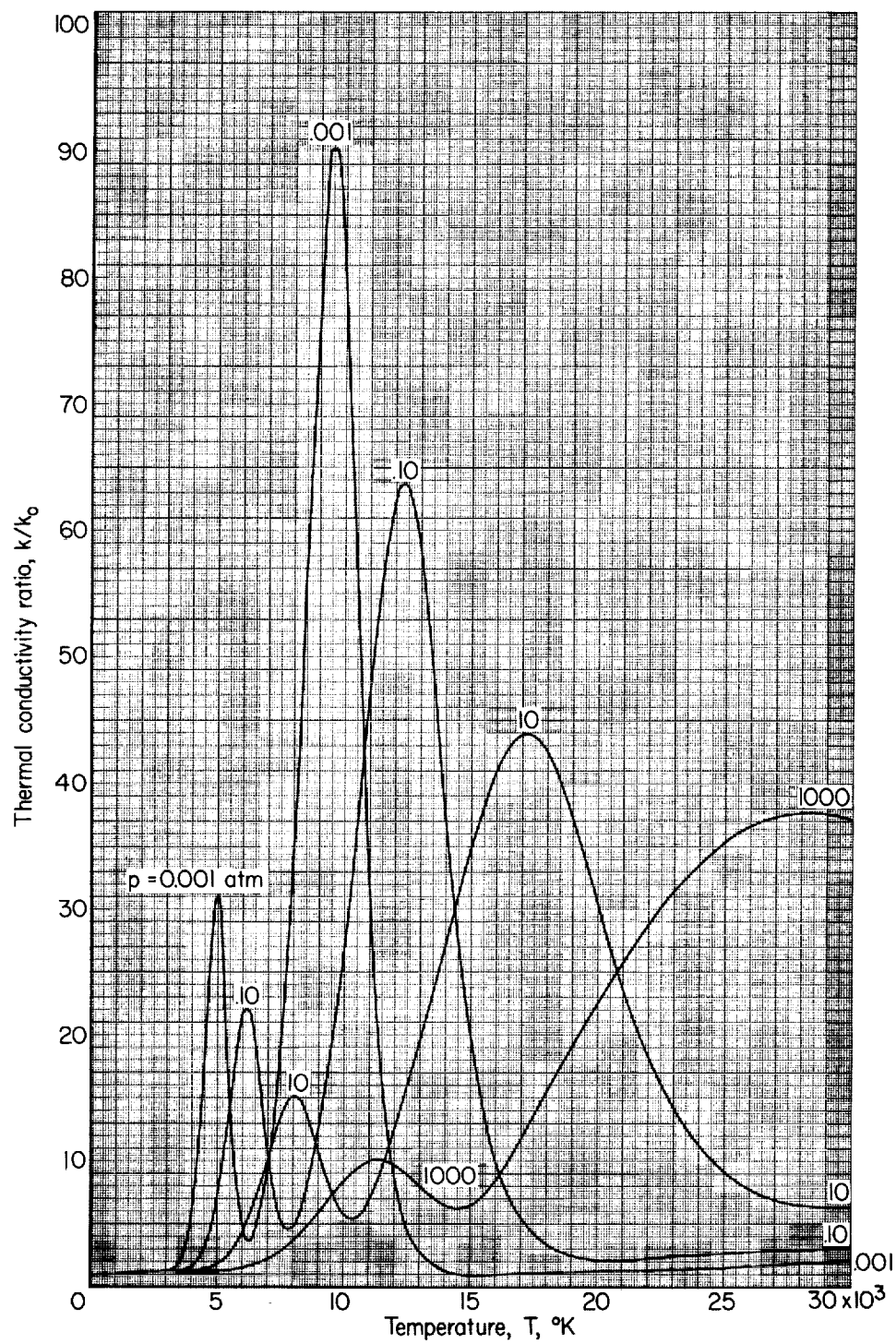
(b) Odd powers of pressure.

Figure 13.- Concluded.
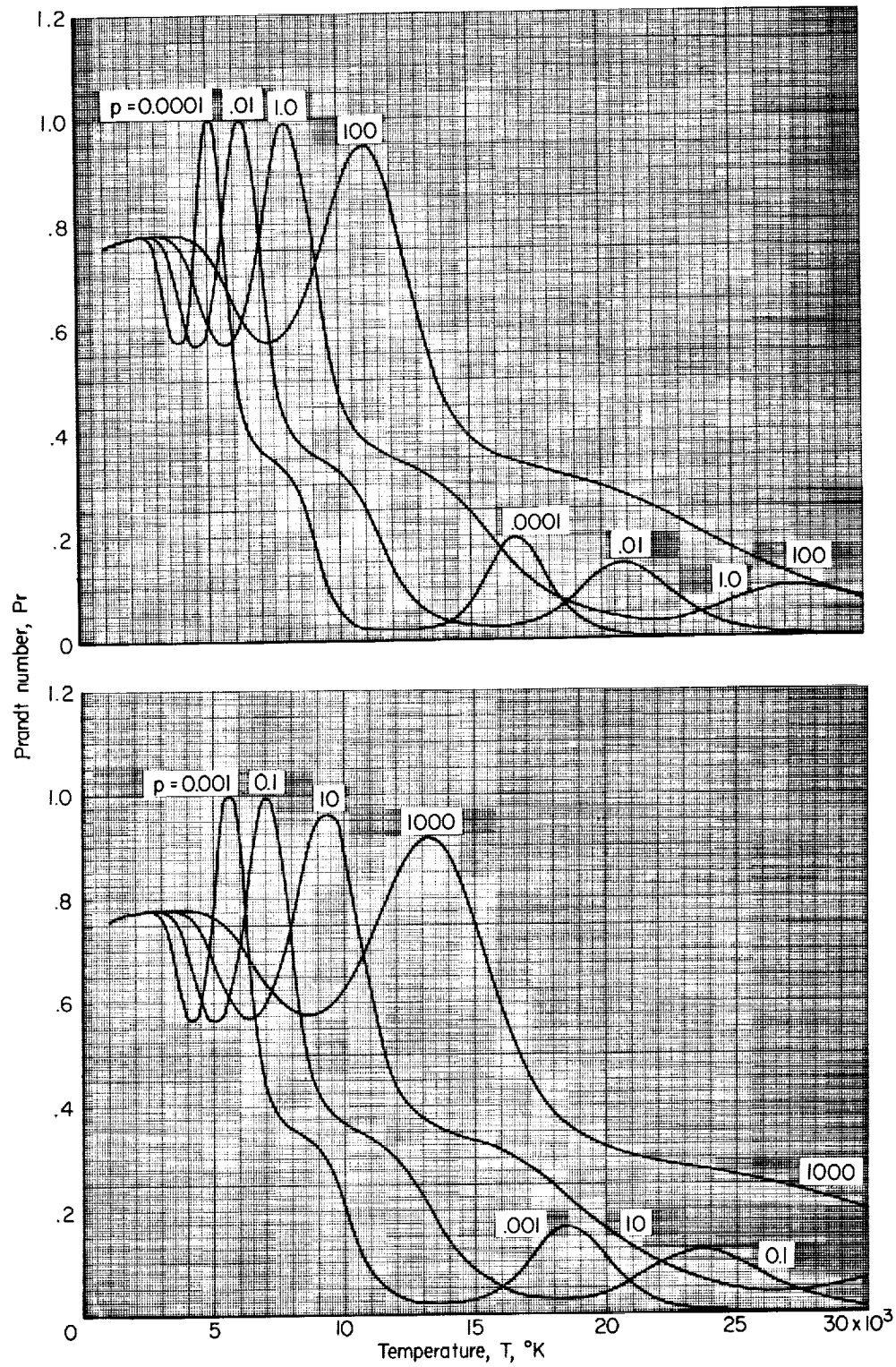
Figure 14.- Prandtl number for nitrogen as a function of temperature.
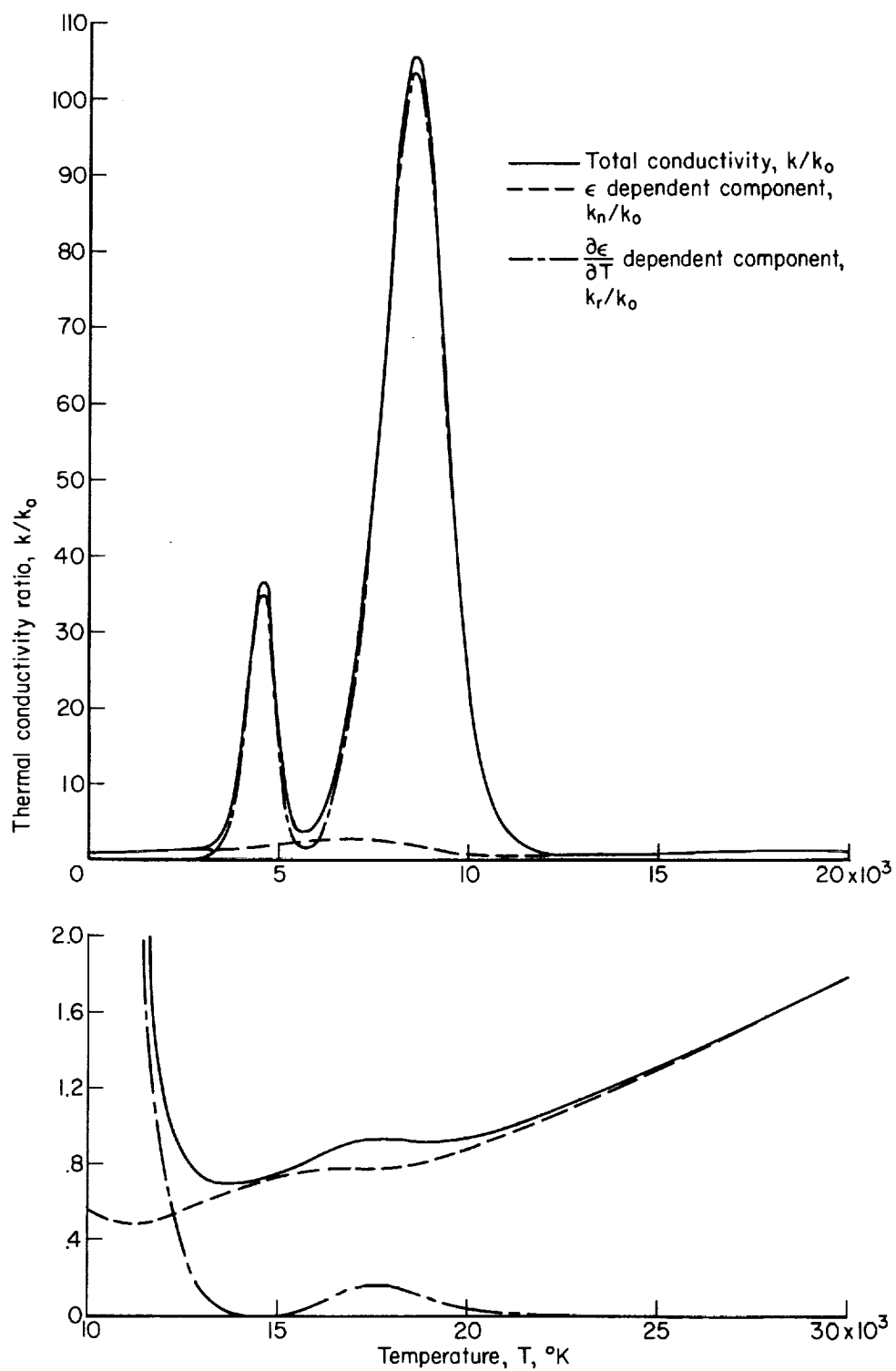
Figure 15.- Components of thermal conductivity ratio for nitrogen.
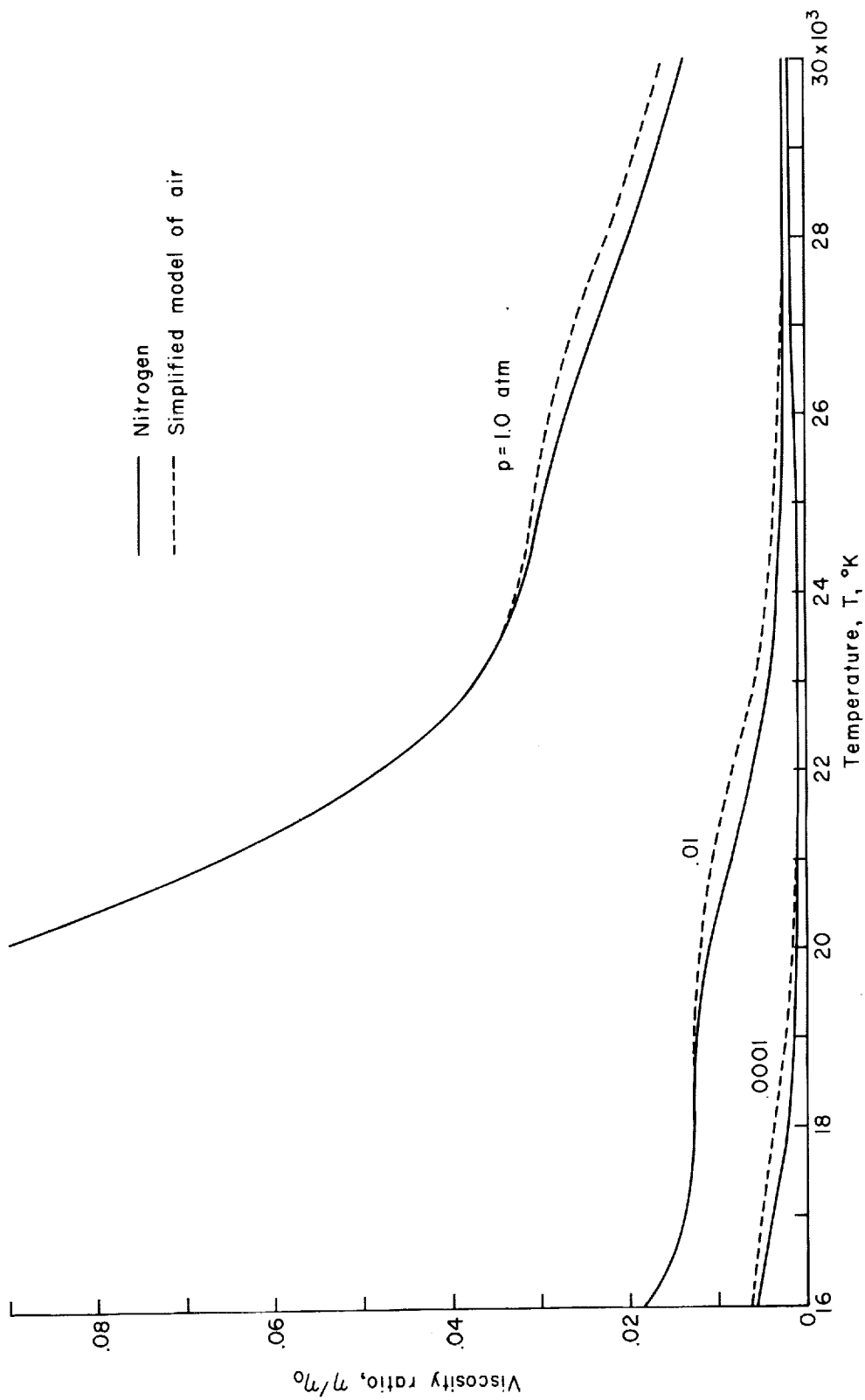
(a) Viscosity ratio.

Figure 16.- Comparison of transport properties for air and nitrogen.
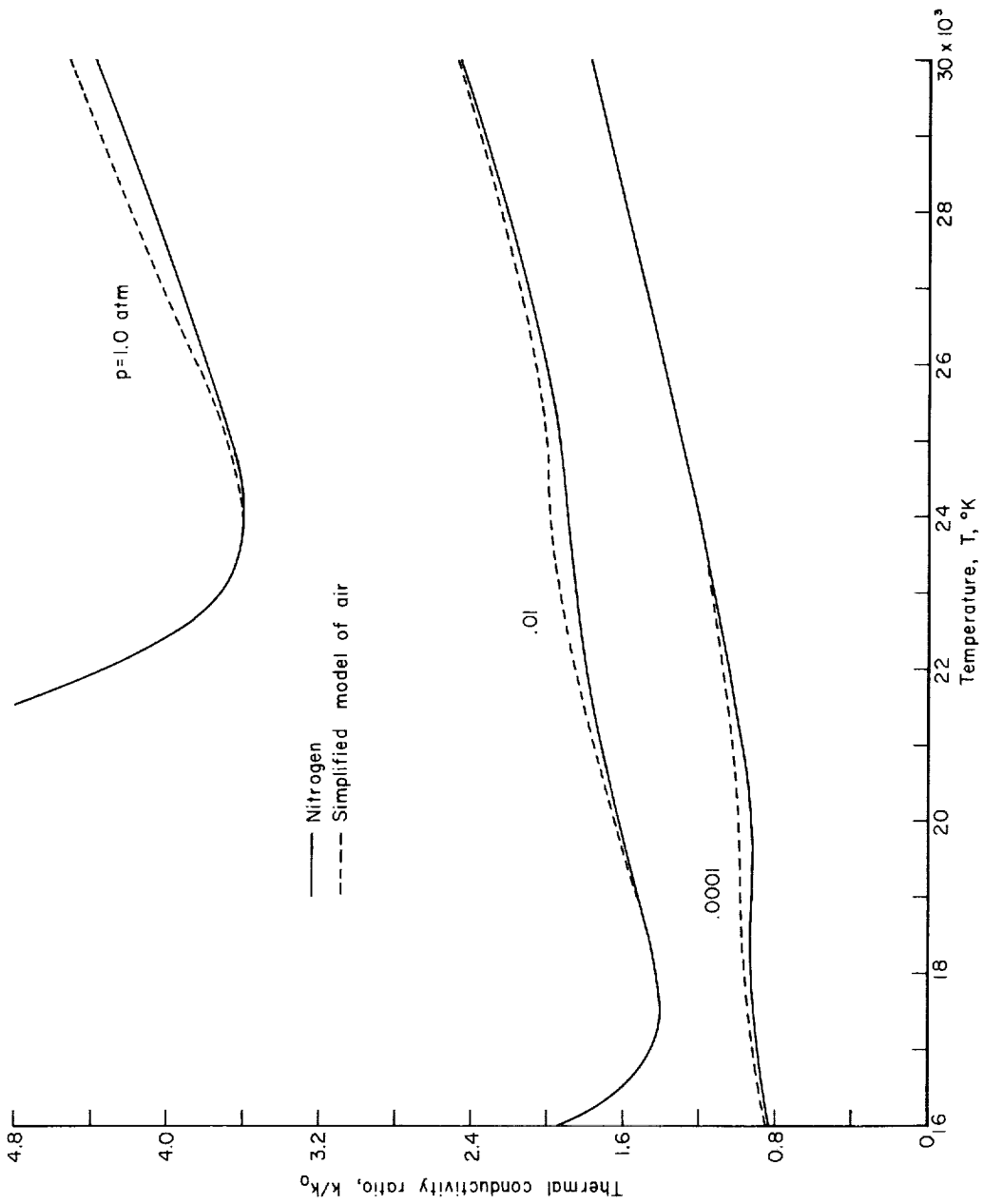
(b) Thermal conductivity ratio.

Figure 16.- Continued.

78
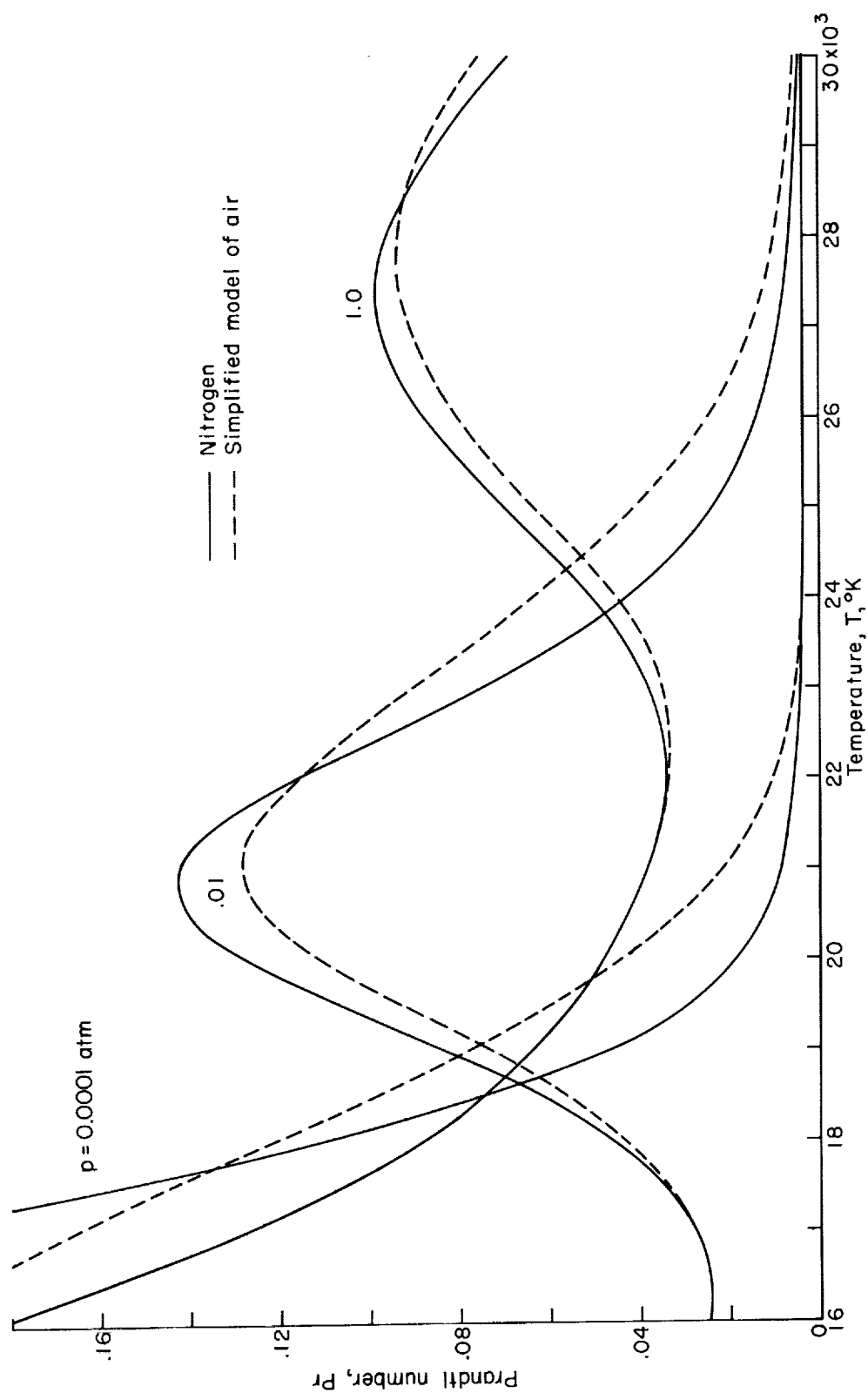
(c) Prandtl number.

Figure 16.- Concluded.
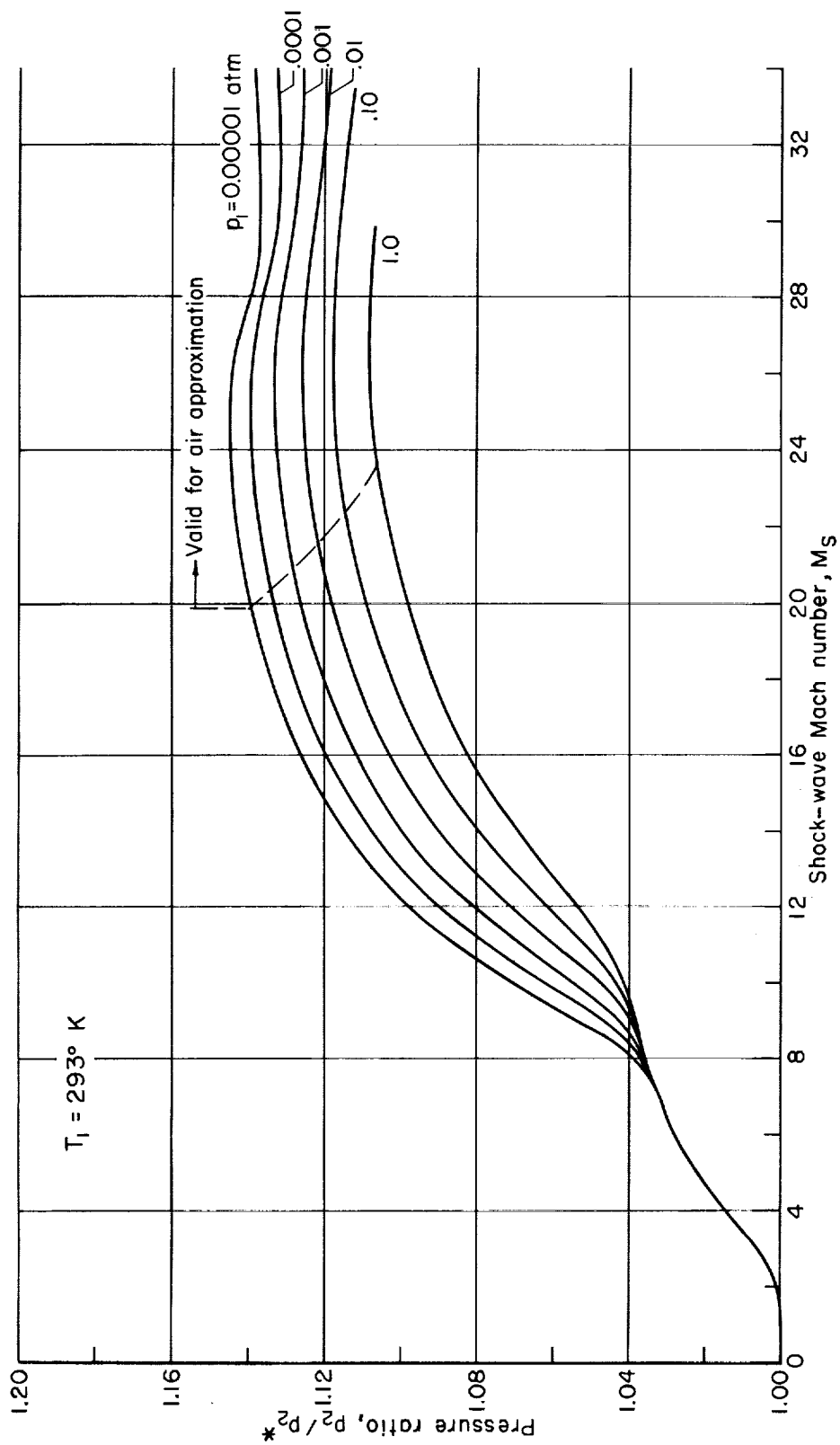
(a) Pressure ratio behind incident shock.

Figure 17.- Equilibrium thermodynamic properties behind incident and reflected shocks for initial temperature of 293° K.
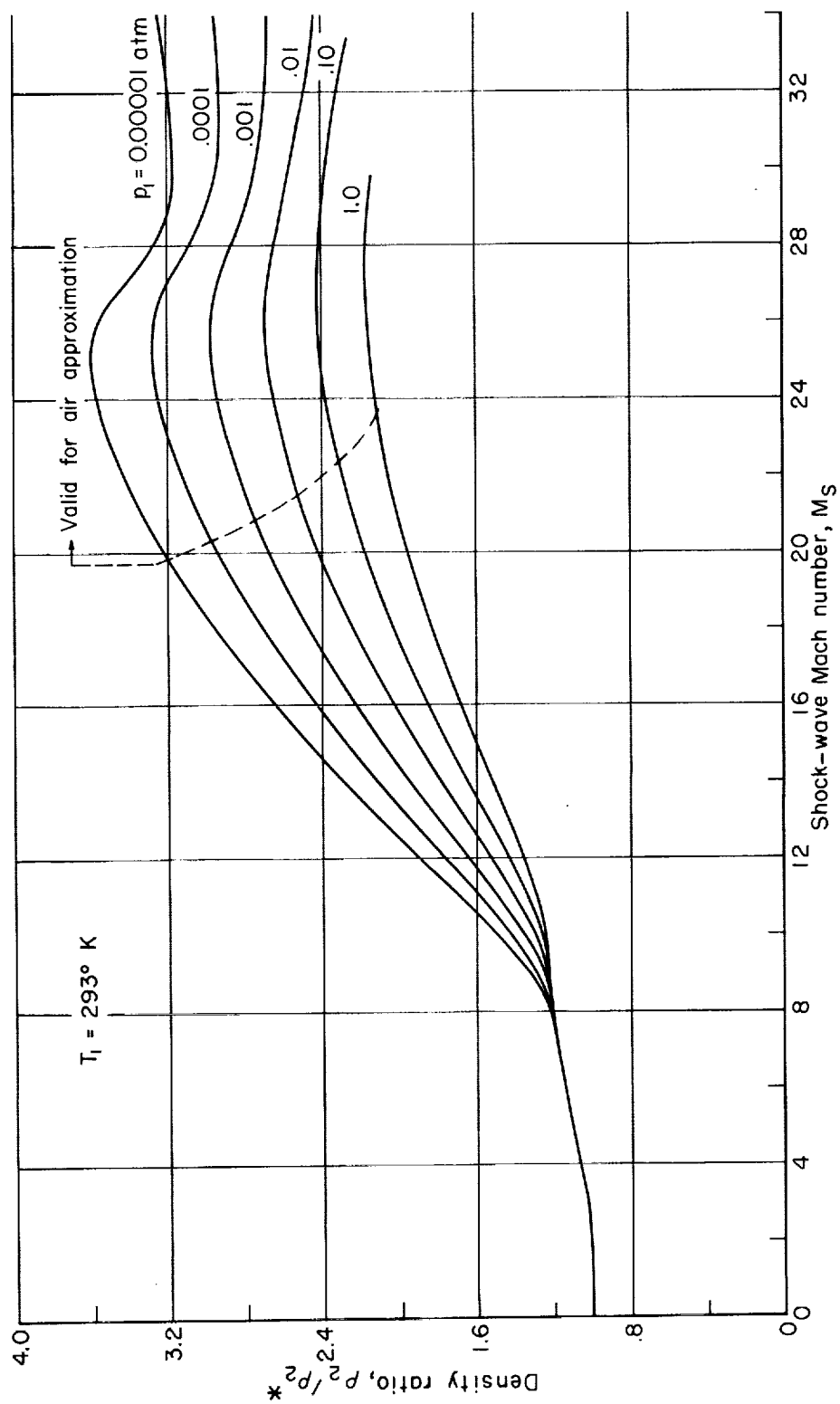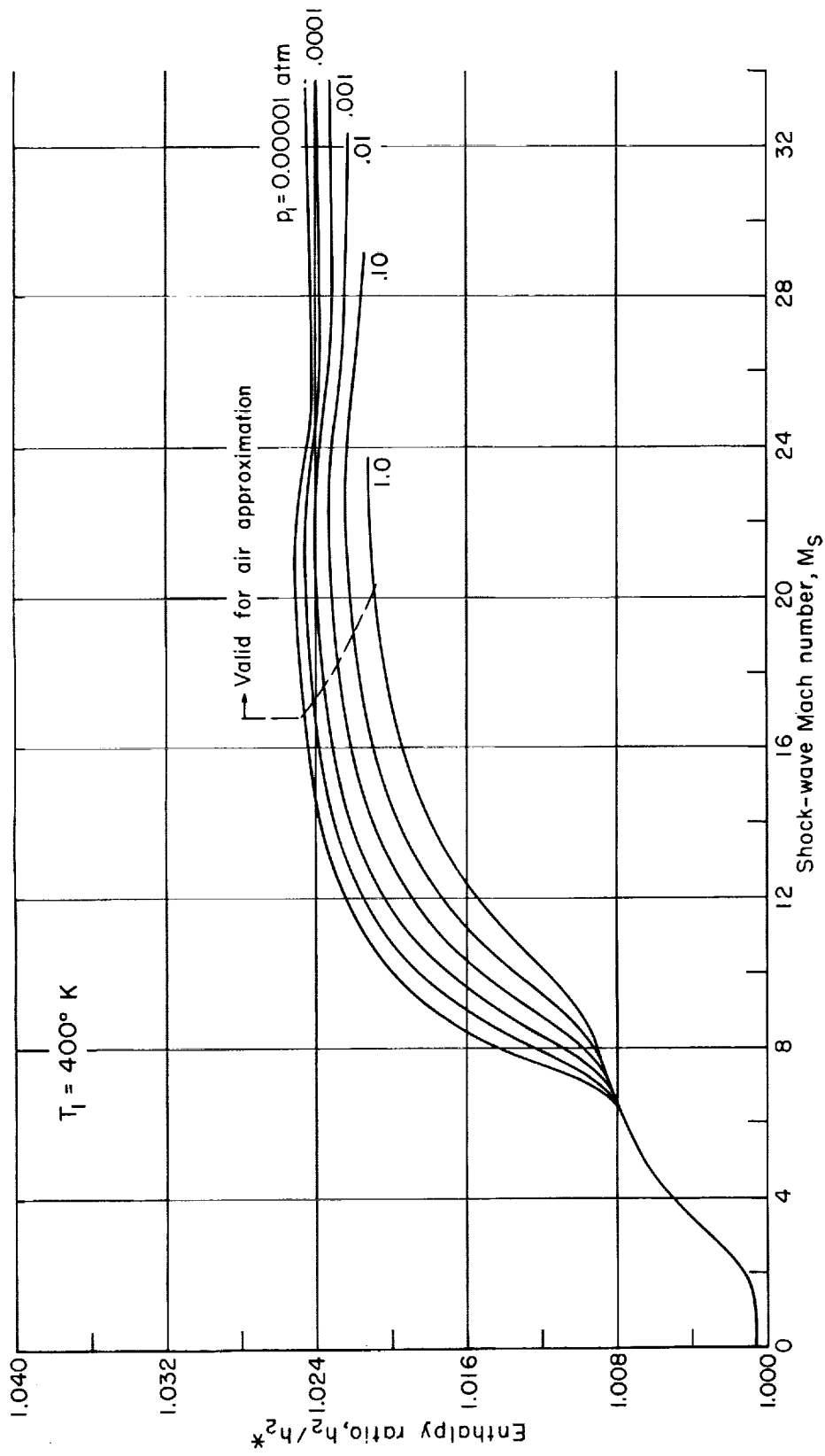
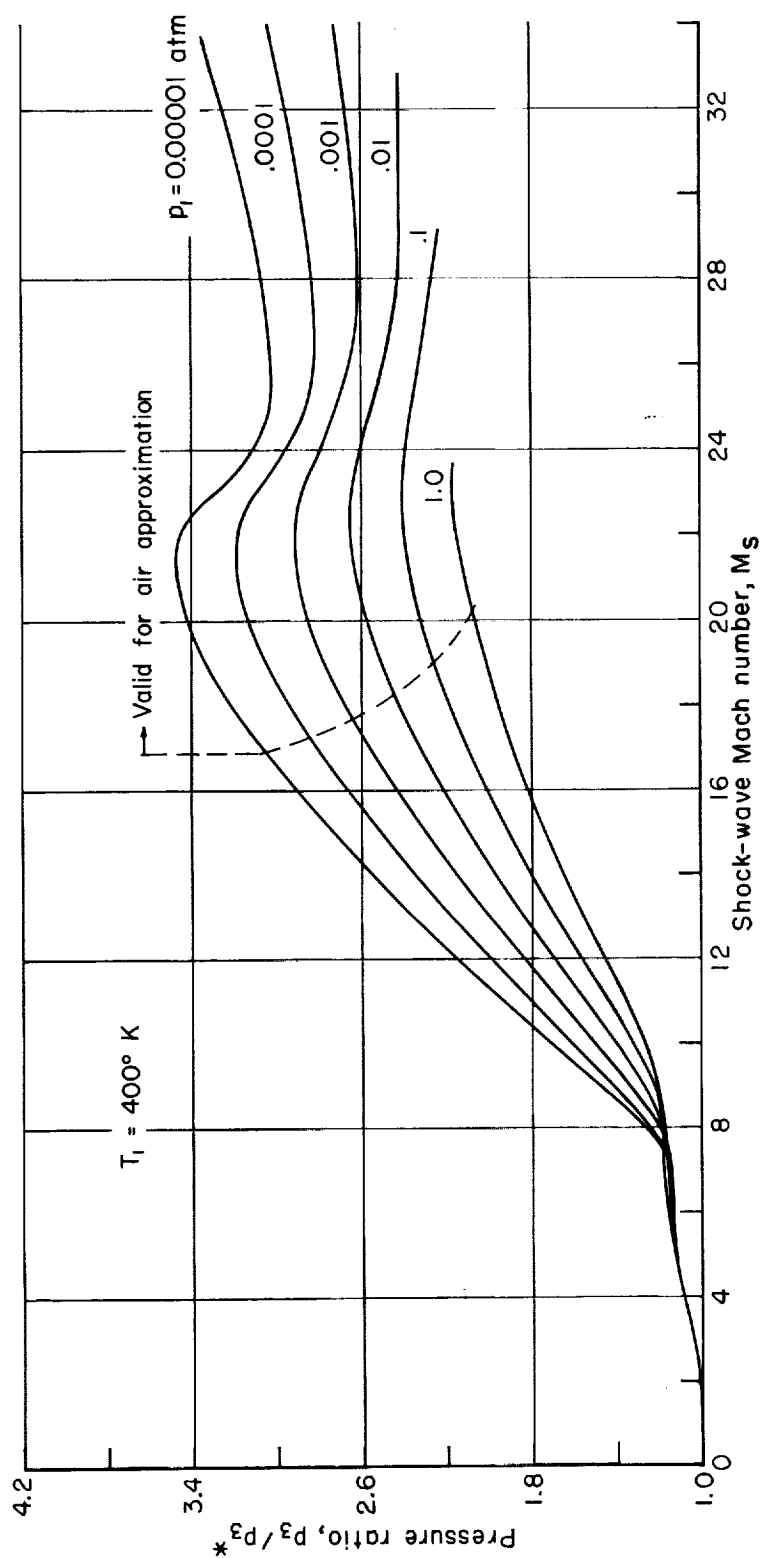(b) Density ratio behind incident shock.

Figure 17.- Continued.

(c) Temperature ratio behind incident shock.
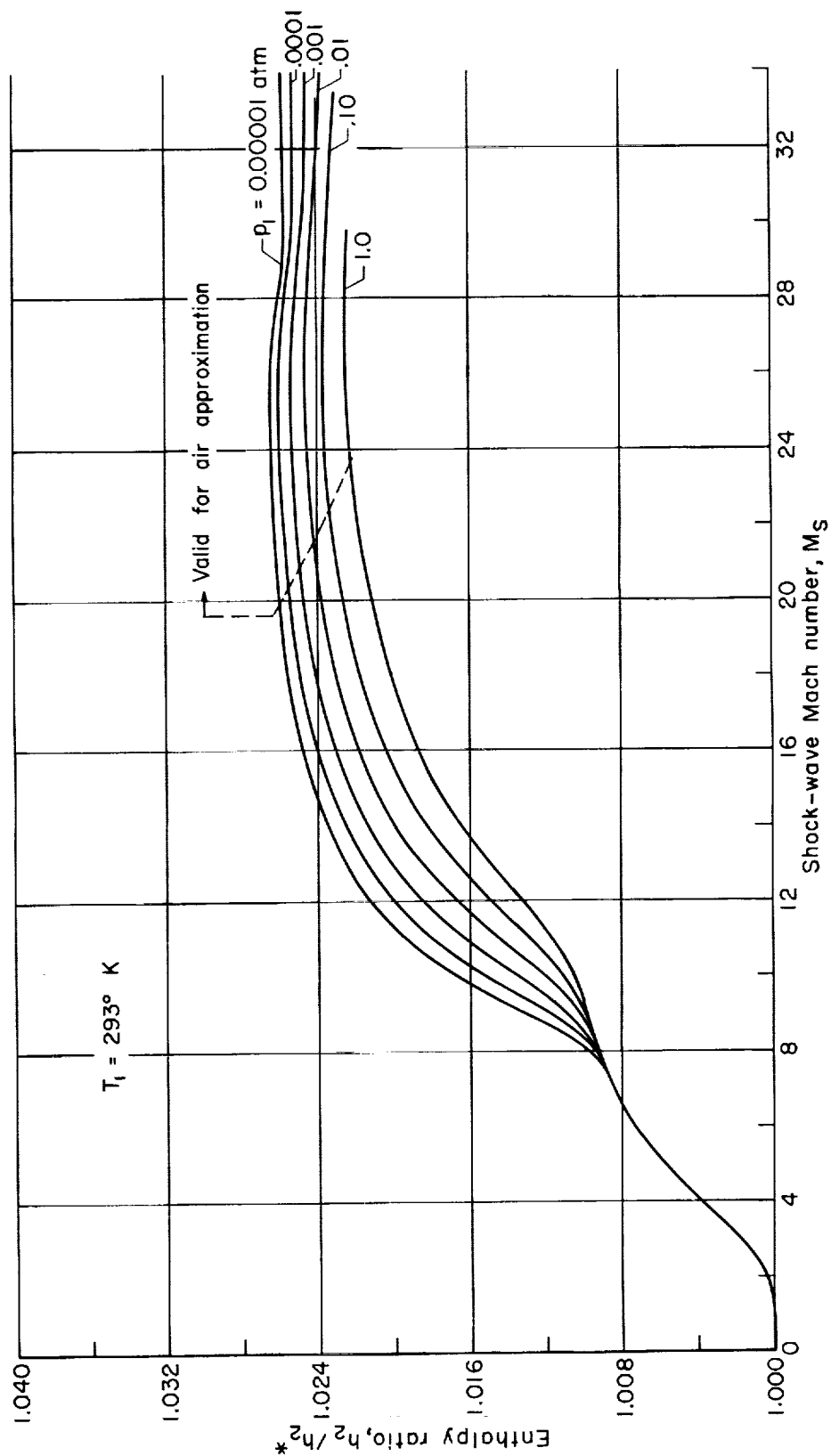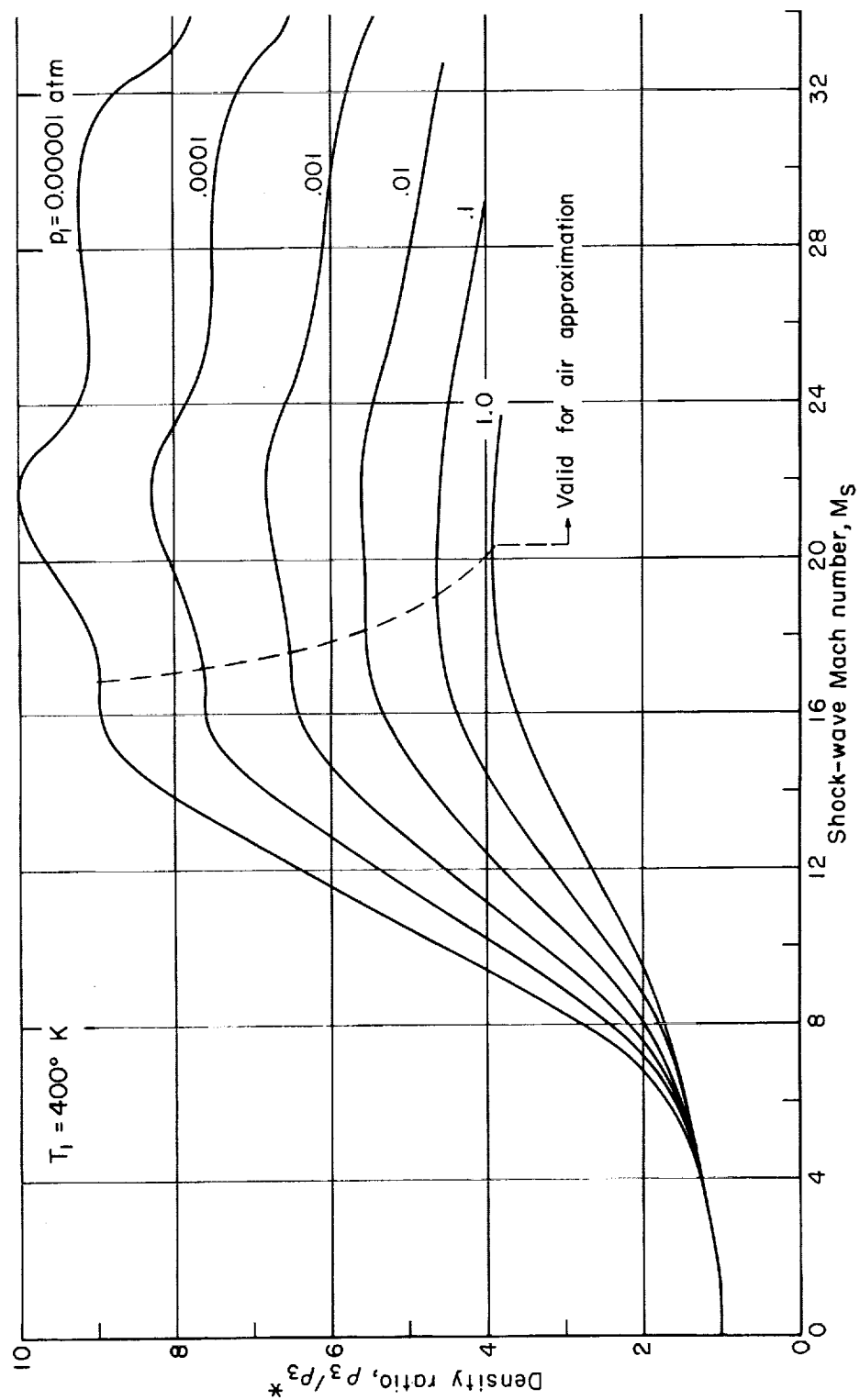
Figure 17.- Continued.

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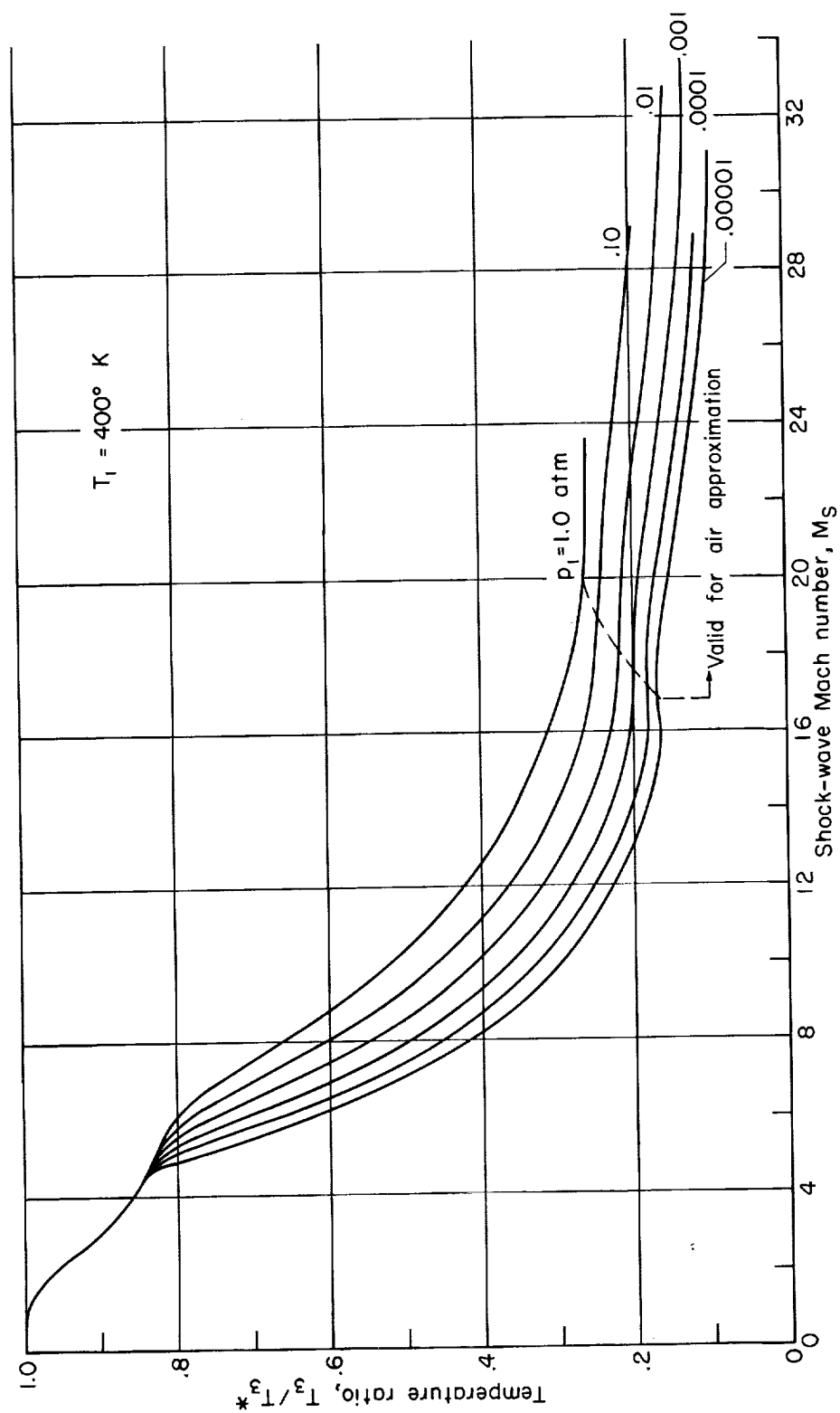(d) Enthalpy ratio behind incident shock.

Figure 17.- Continued.

83

(e) Pressure ratio behind reflected shock.
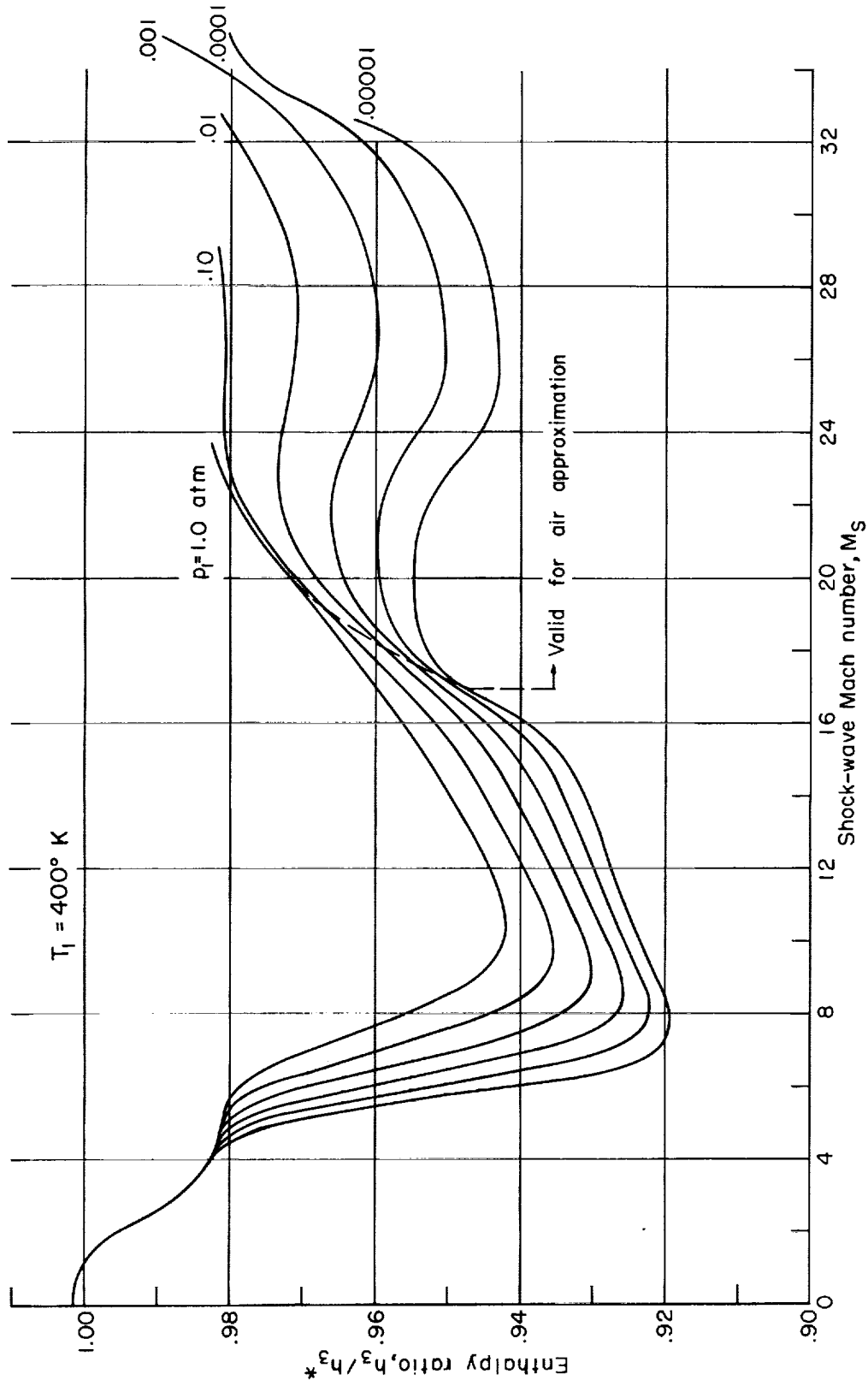
Figure 17.- Continued.

(f) Density ratio behind reflected shock.

Figure 17.- Continued.
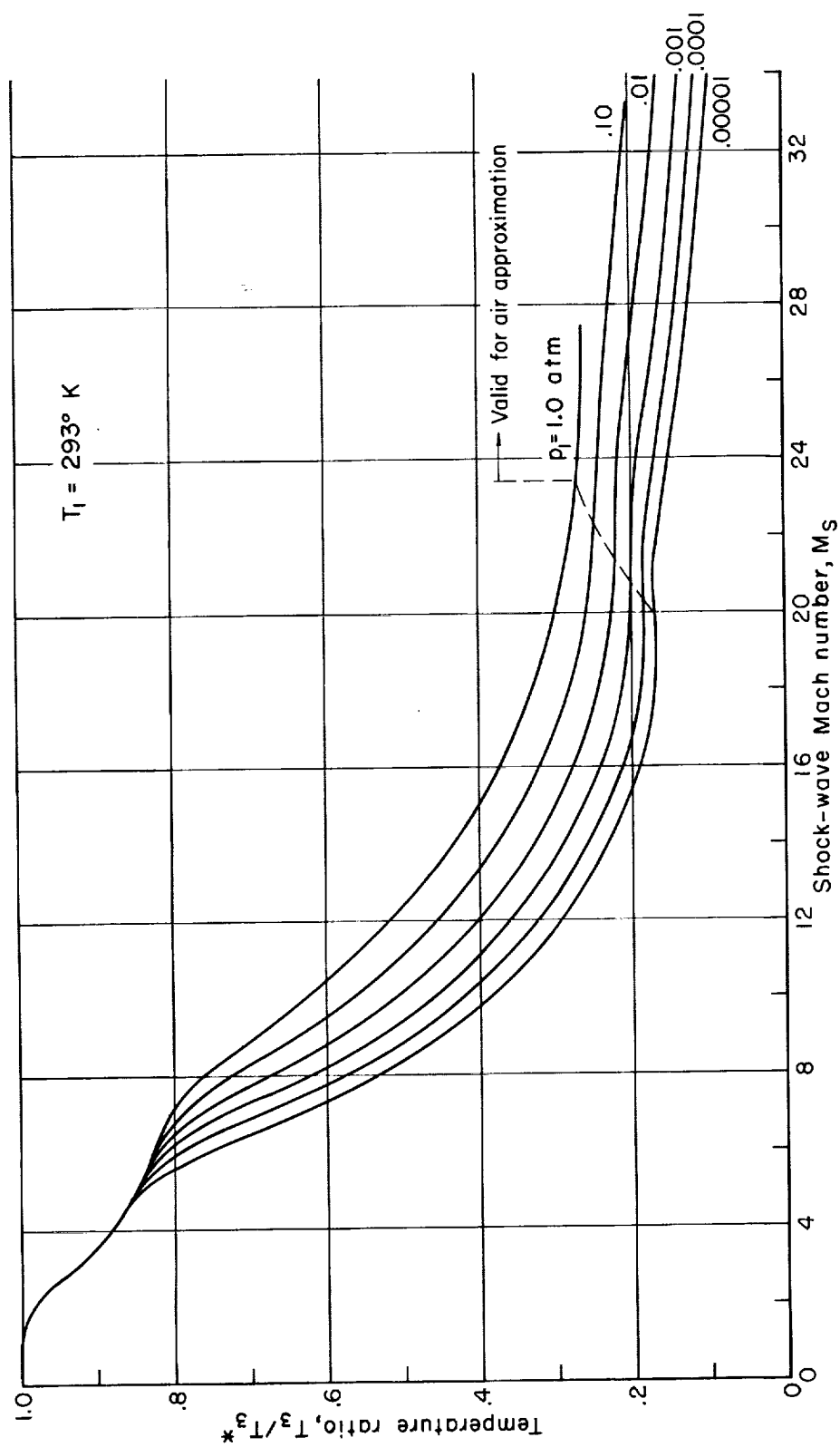
(g) Temperature ratio behind reflected shock.

Figure 17.- Continued.
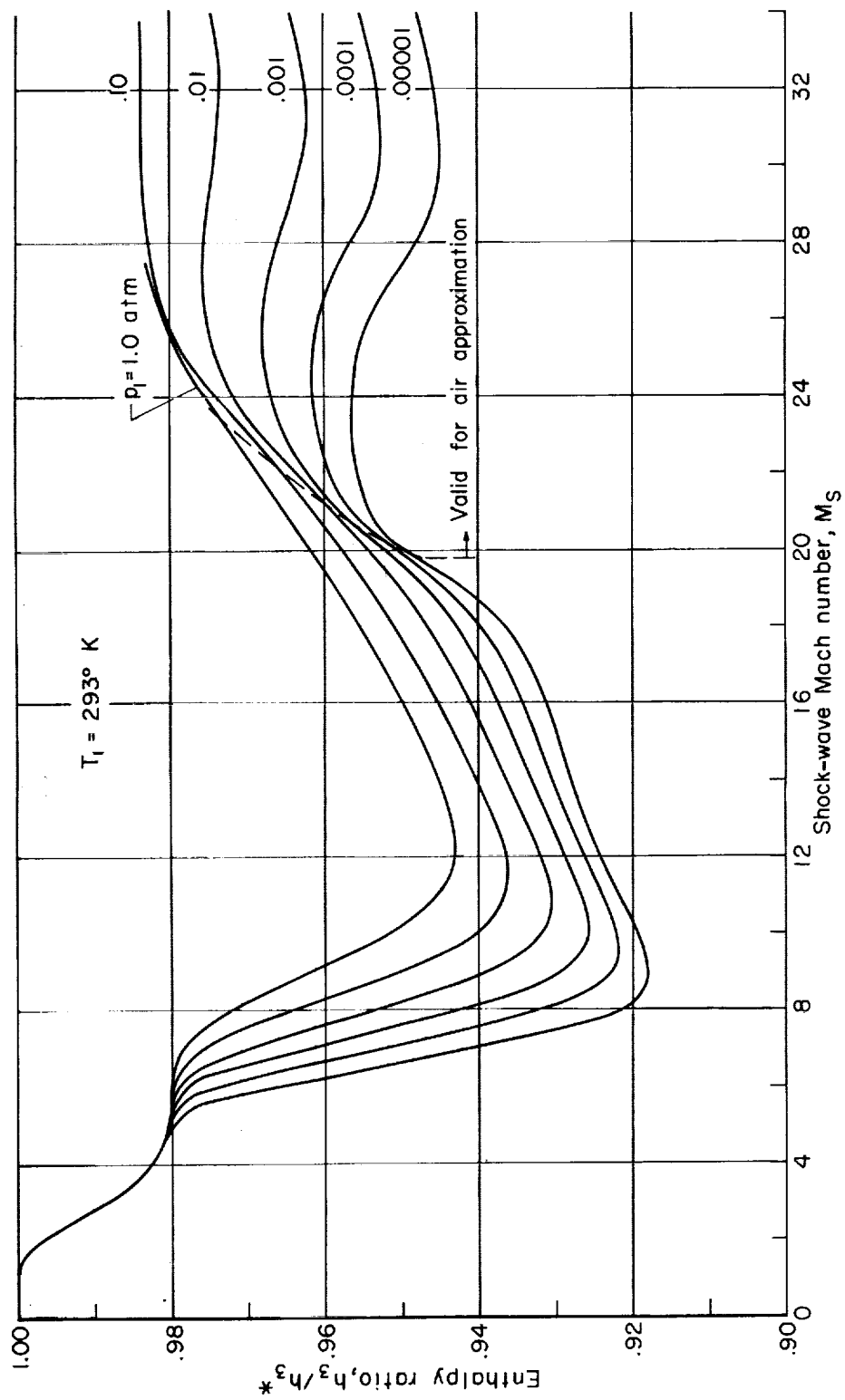
(h) Enthalpy ratio behind reflected shock.

Figure 17.- Concluded.
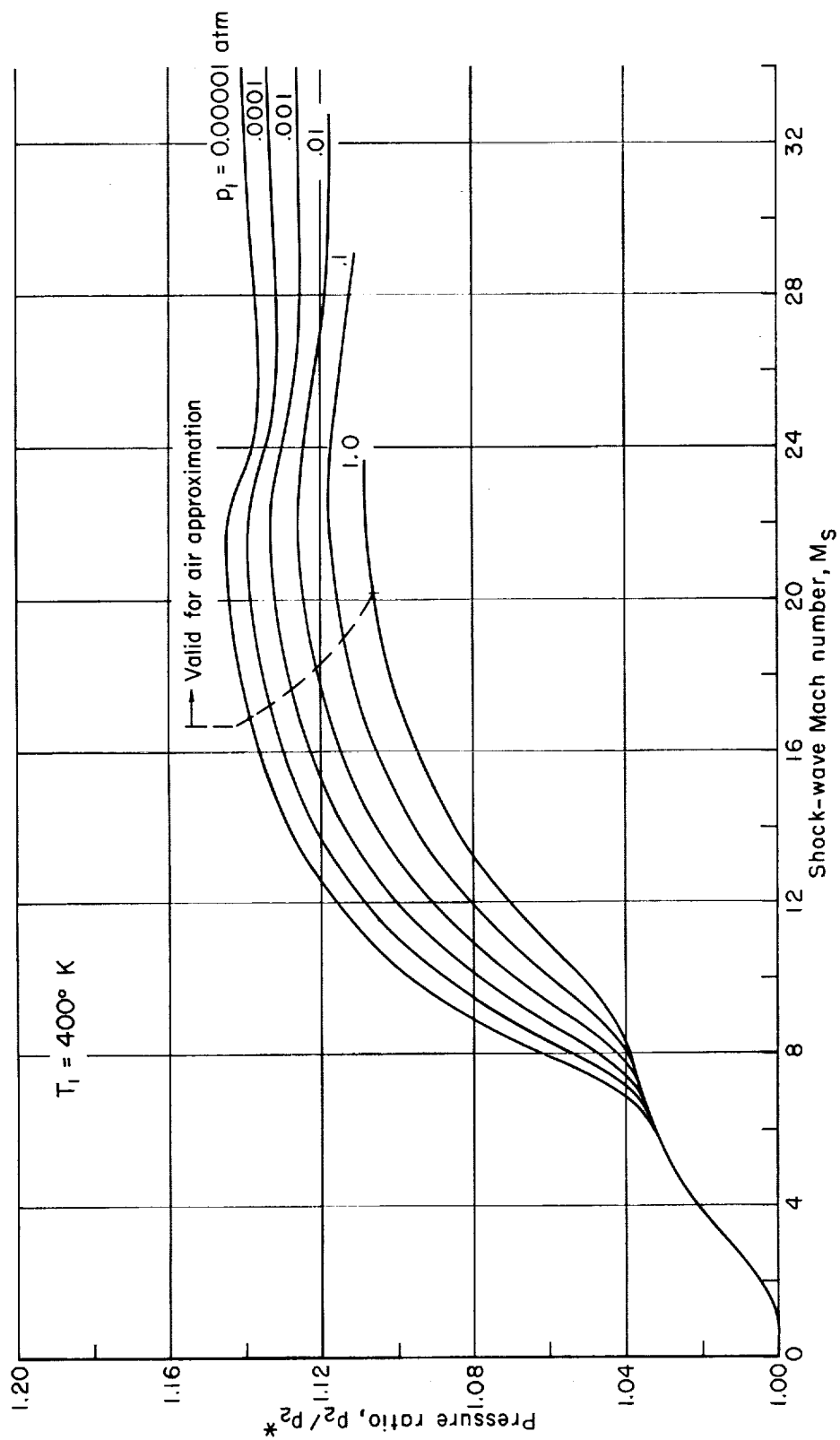
(a) Pressure ratio behind incident shock.

Figure 18.- Equilibrium thermodynamic properties behind incident and reflected shocks for initial temperature of 400° K.
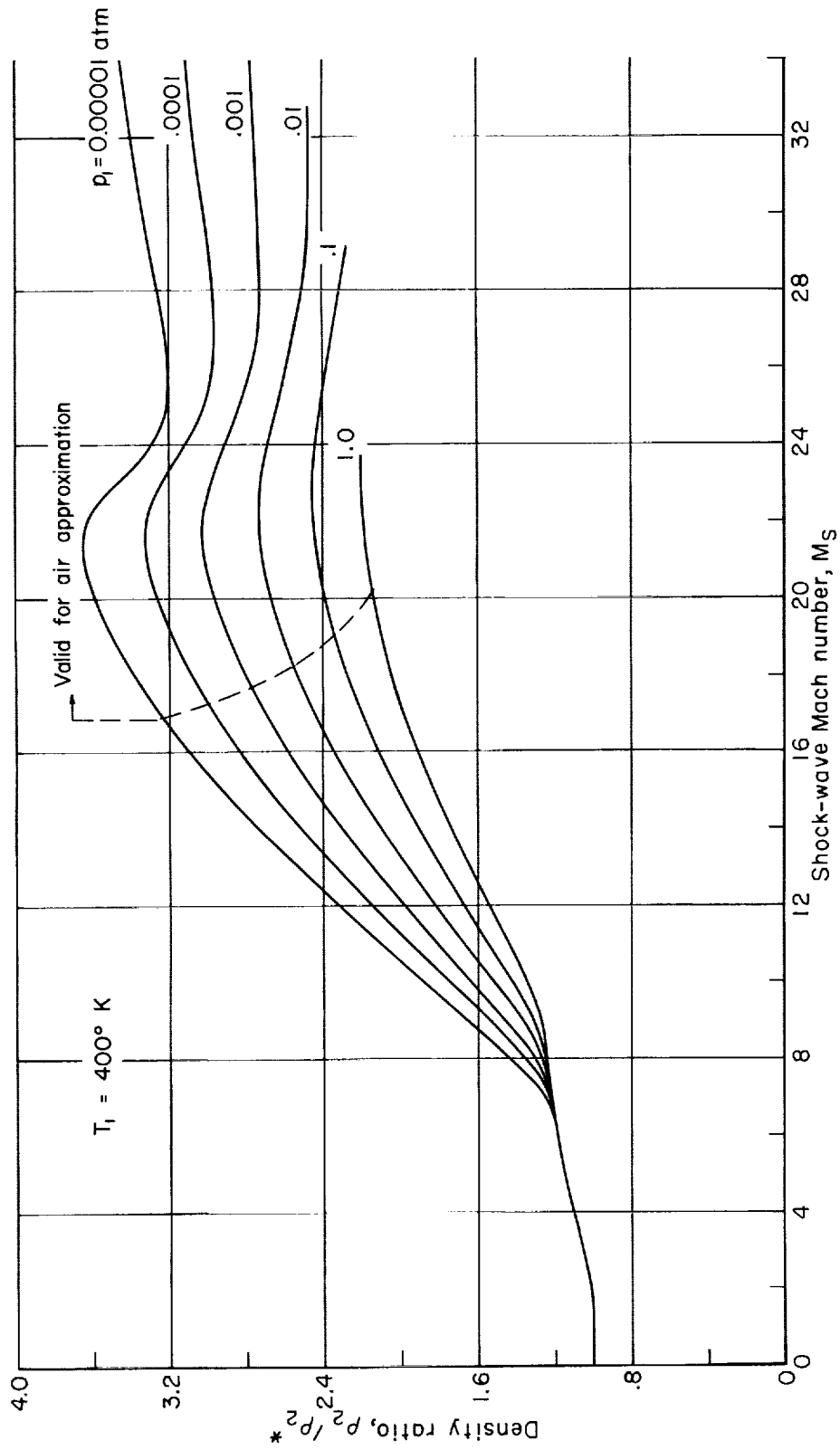
(b) Density ratio behind incident shock.
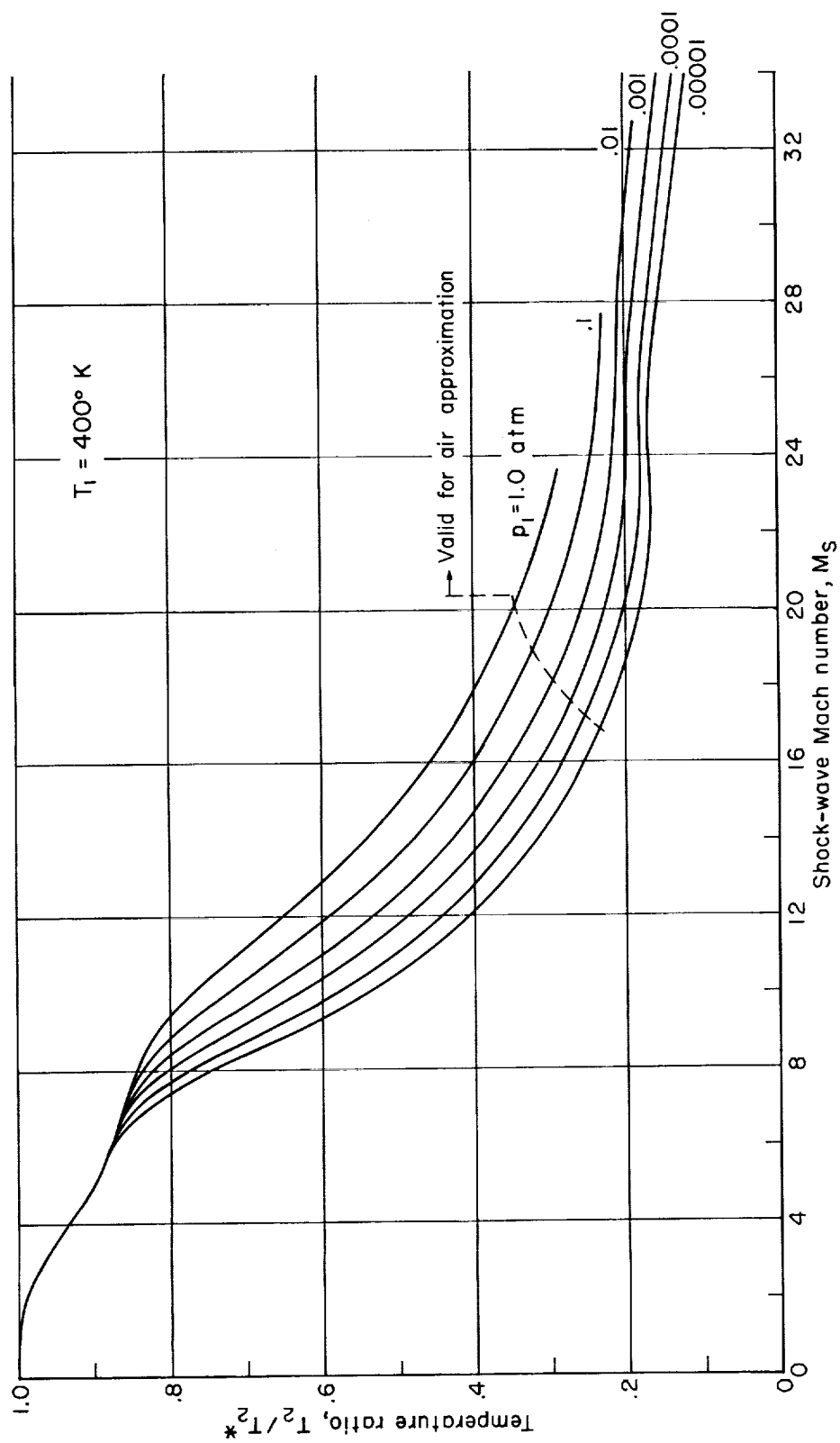
Figure 18.- Continued.

$T_1 = 400°$ K

Valid for air approximation

$p_1 = 1.0$ atm

.1

.01

.001

.0001

.00001

.10000

Shock-wave Mach number, M_s

Temperature ratio, T_2/T_2^*

(c) Temperature ratio behind incident shock.

Figure 18.- Continued.

90

(d) Enthalpy ratio behind incident shock.

Figure 18.- Continued.

(e) Pressure ratio behind reflected shock.

Figure 18. - Continued.

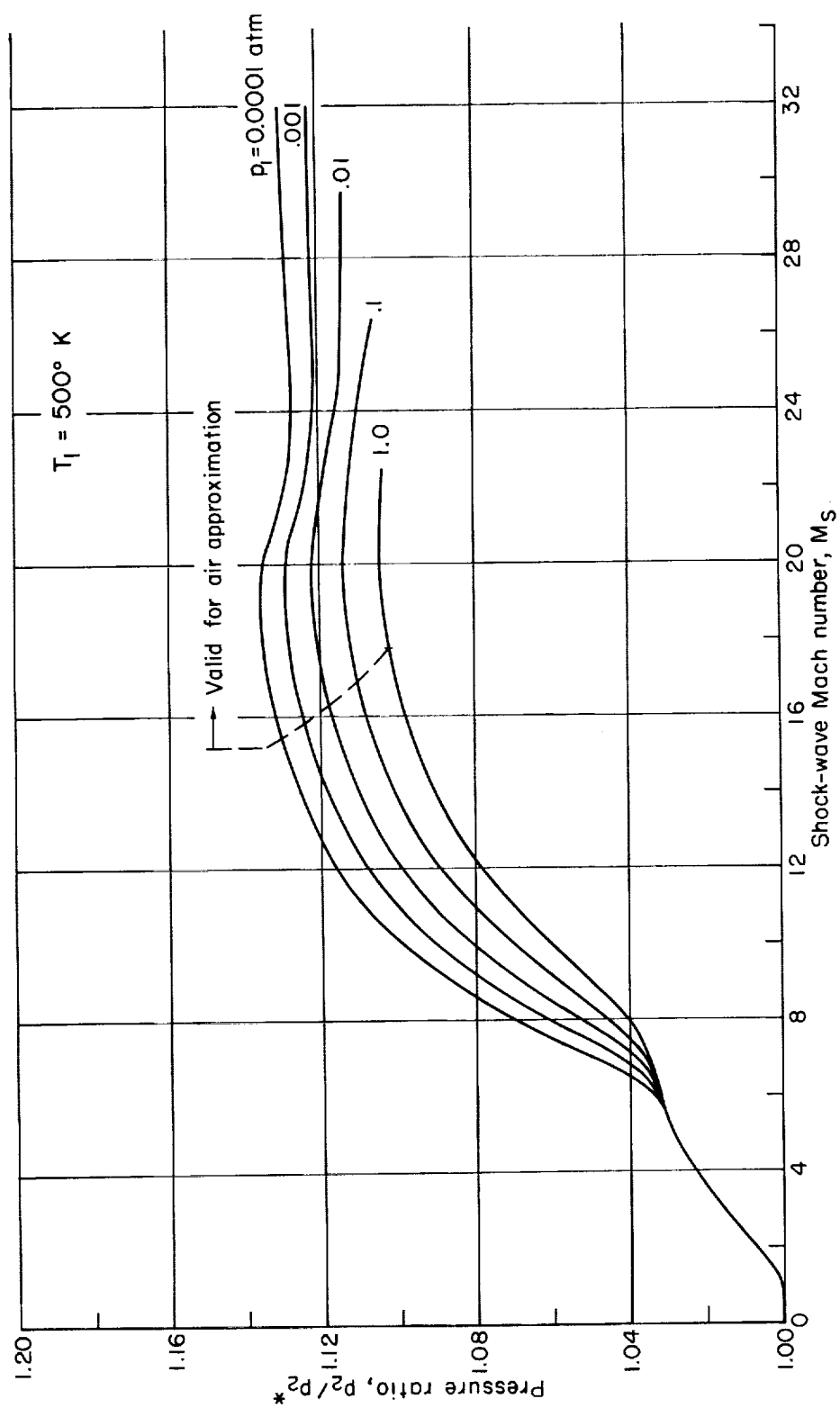(f) Density ratio behind reflected shock.

Figure 18.- Continued.

$T_1 = 400°$ K

$p_1 = 1.0$ atm

Valid for air approximation

.10

.01

.001

.0001

.00001

Shock-wave Mach number, M_S

Temperature ratio, T_3/T_3*

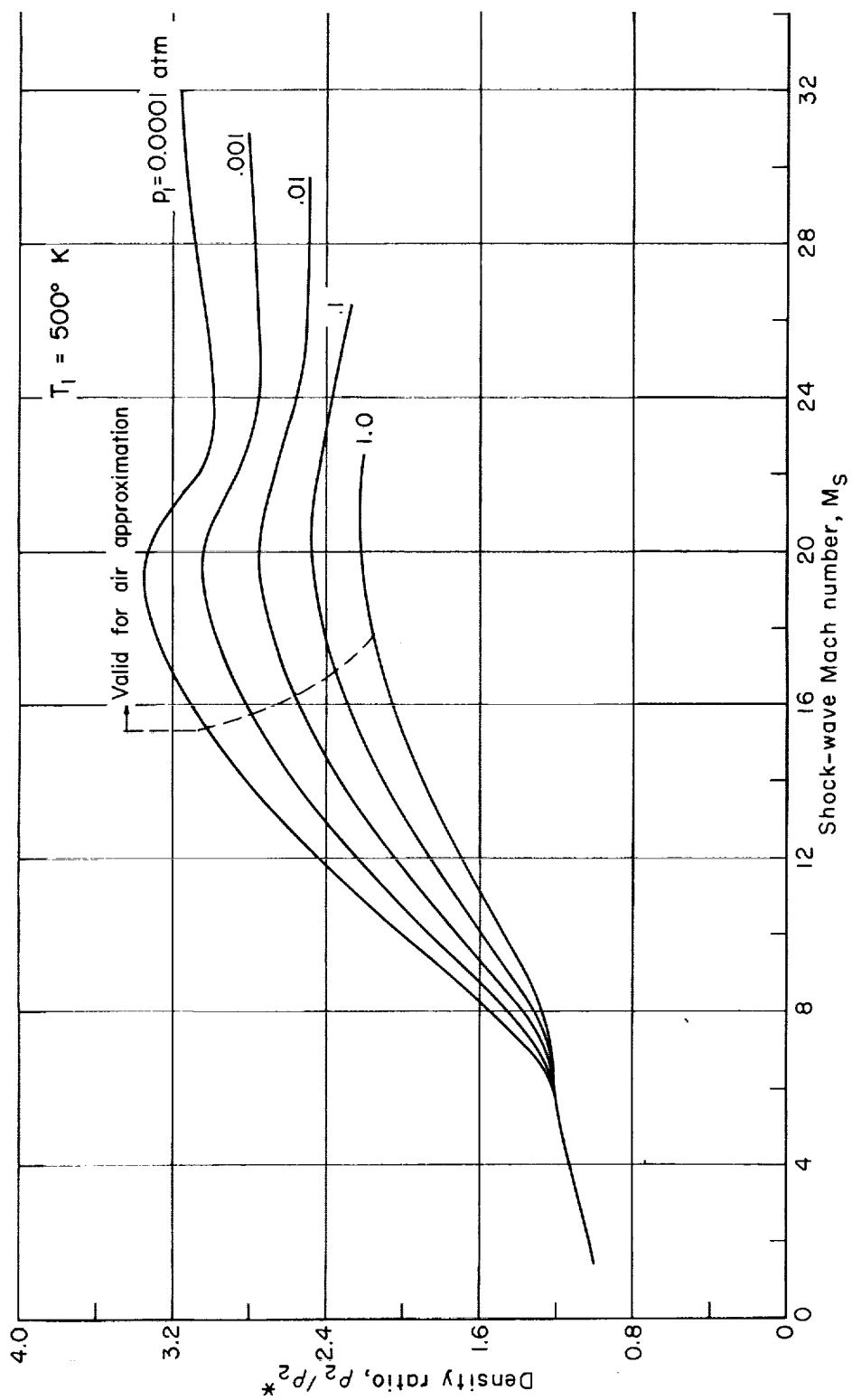(g) Temperature ratio behind reflected shock.

Figure 18.- Continued.

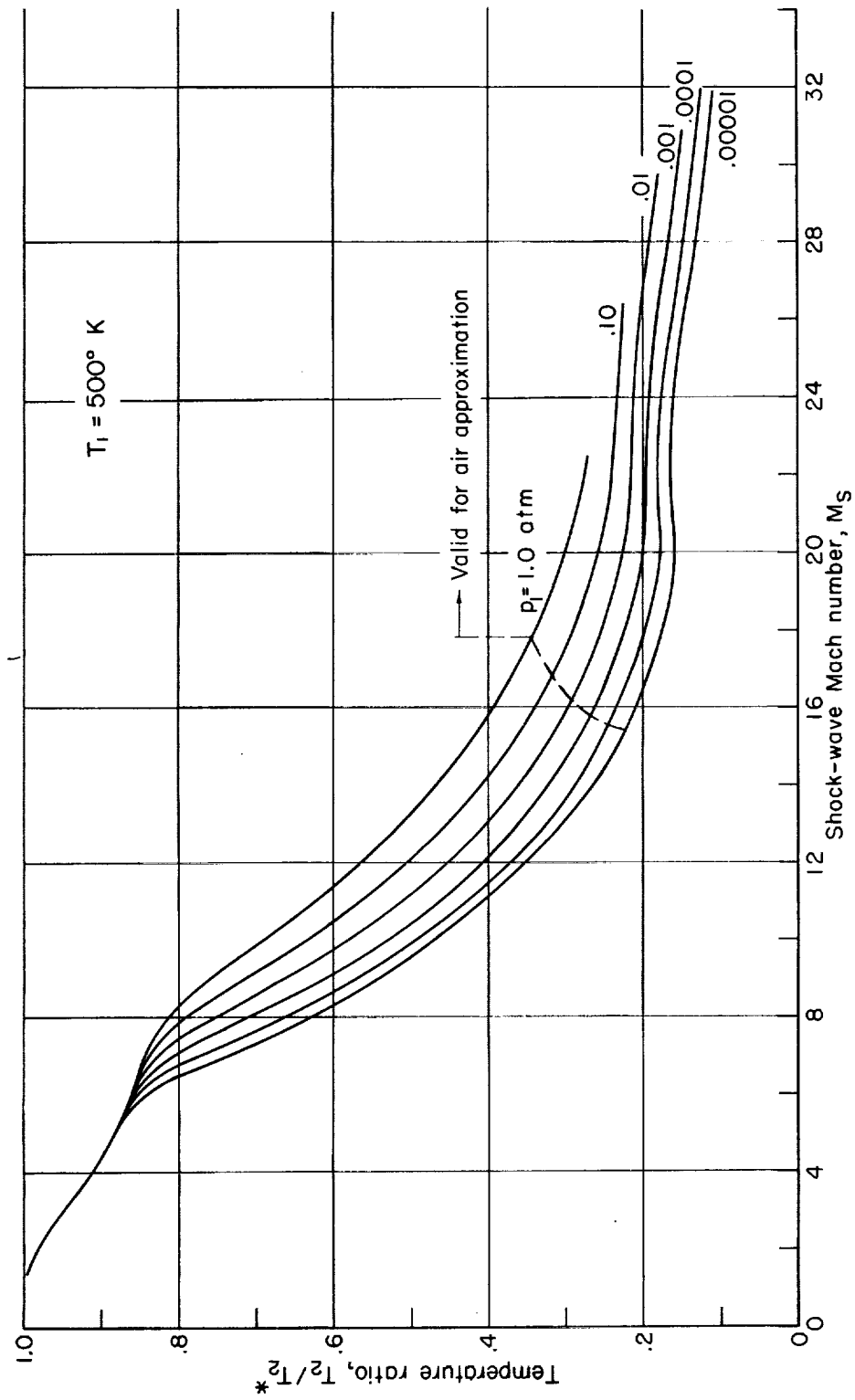(h) Enthalpy ratio behind reflected shock.

Figure 18.- Concluded.

(a) Pressure ratio behind incident shock.

Figure 19.- Equilibrium thermodynamic properties behind incident and reflected shocks for initial temperature of 500° K.
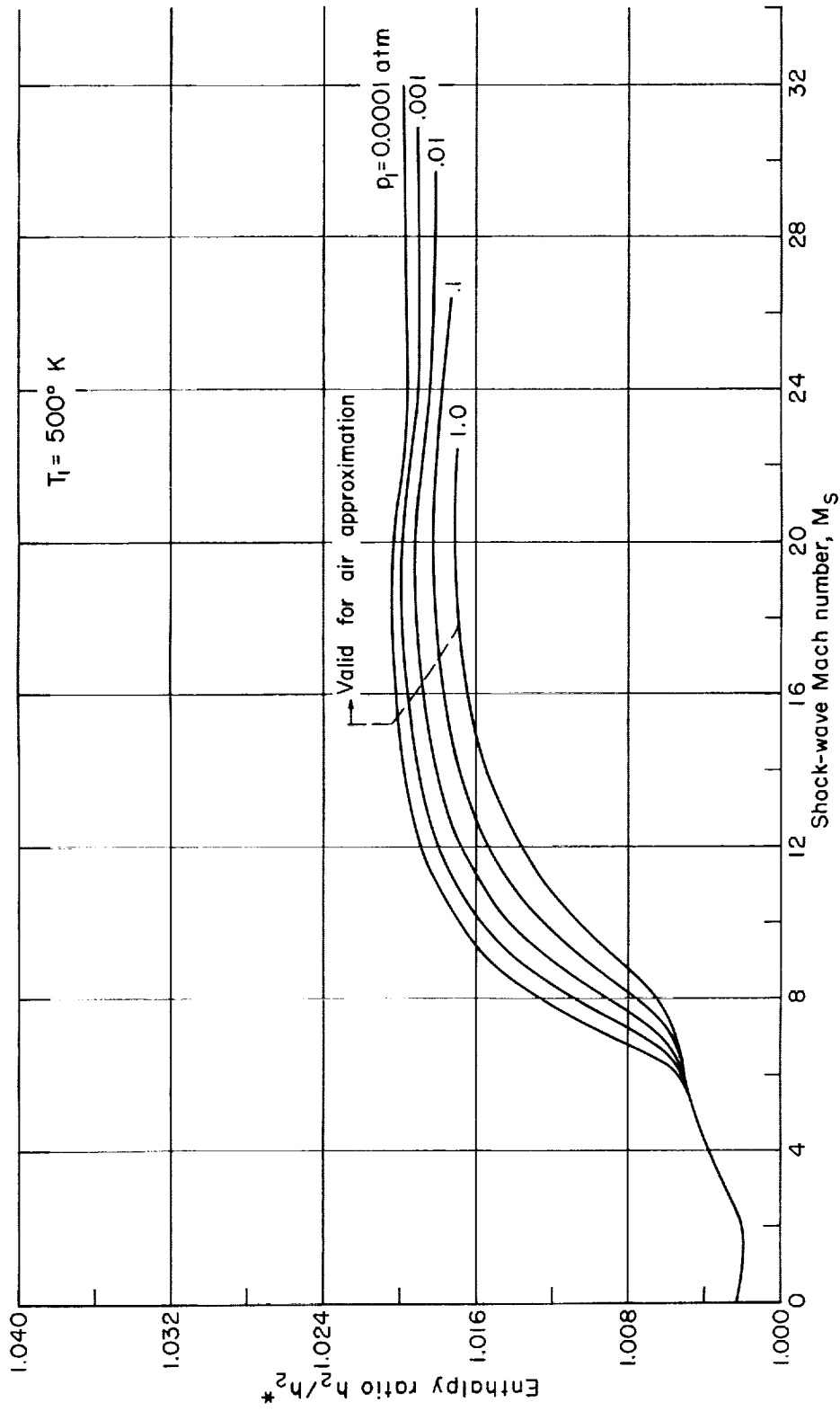
(b) Density ratio behind incident shock.
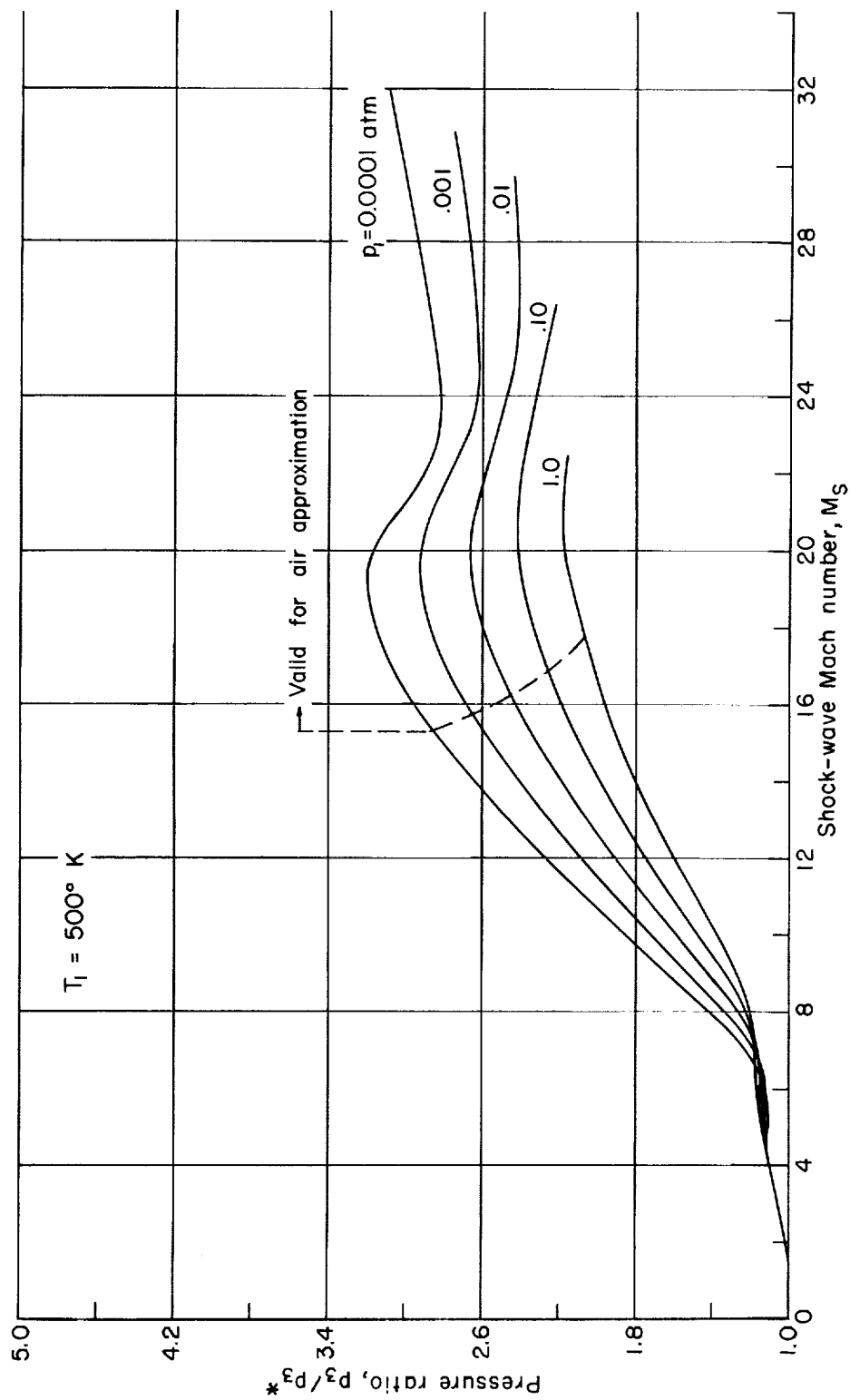
Figure 19.- Continued.

(c) Temperature ratio behind incident shock.

Figure 19.- Continued.

(d) Enthalpy ratio behind incident shock.

Figure 19.- Continued.

(e) Pressure ratio behind reflected shock.

Figure 19.- Continued.

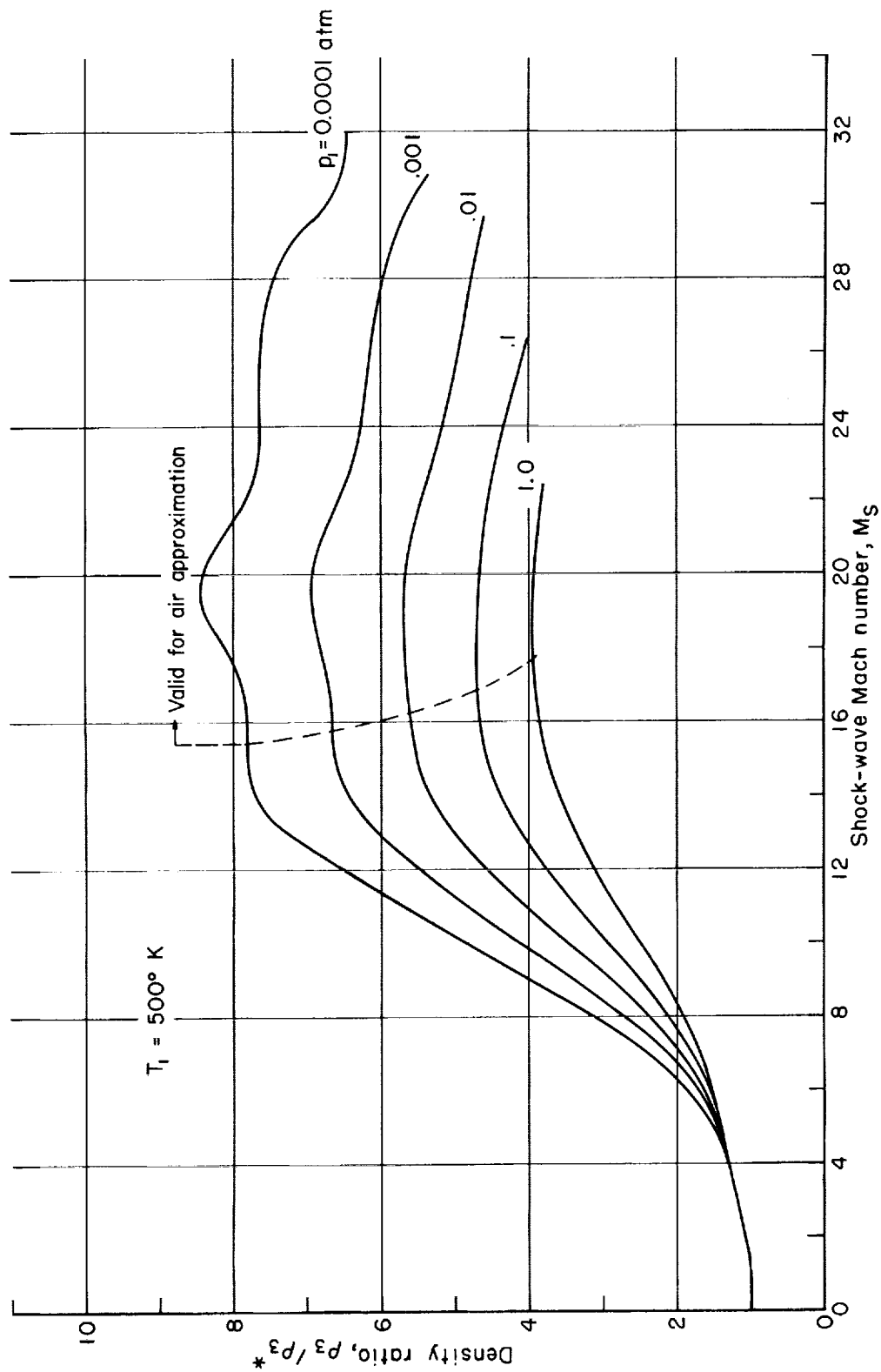(f) Density ratio behind reflected shock.

Figure 19.- Continued.
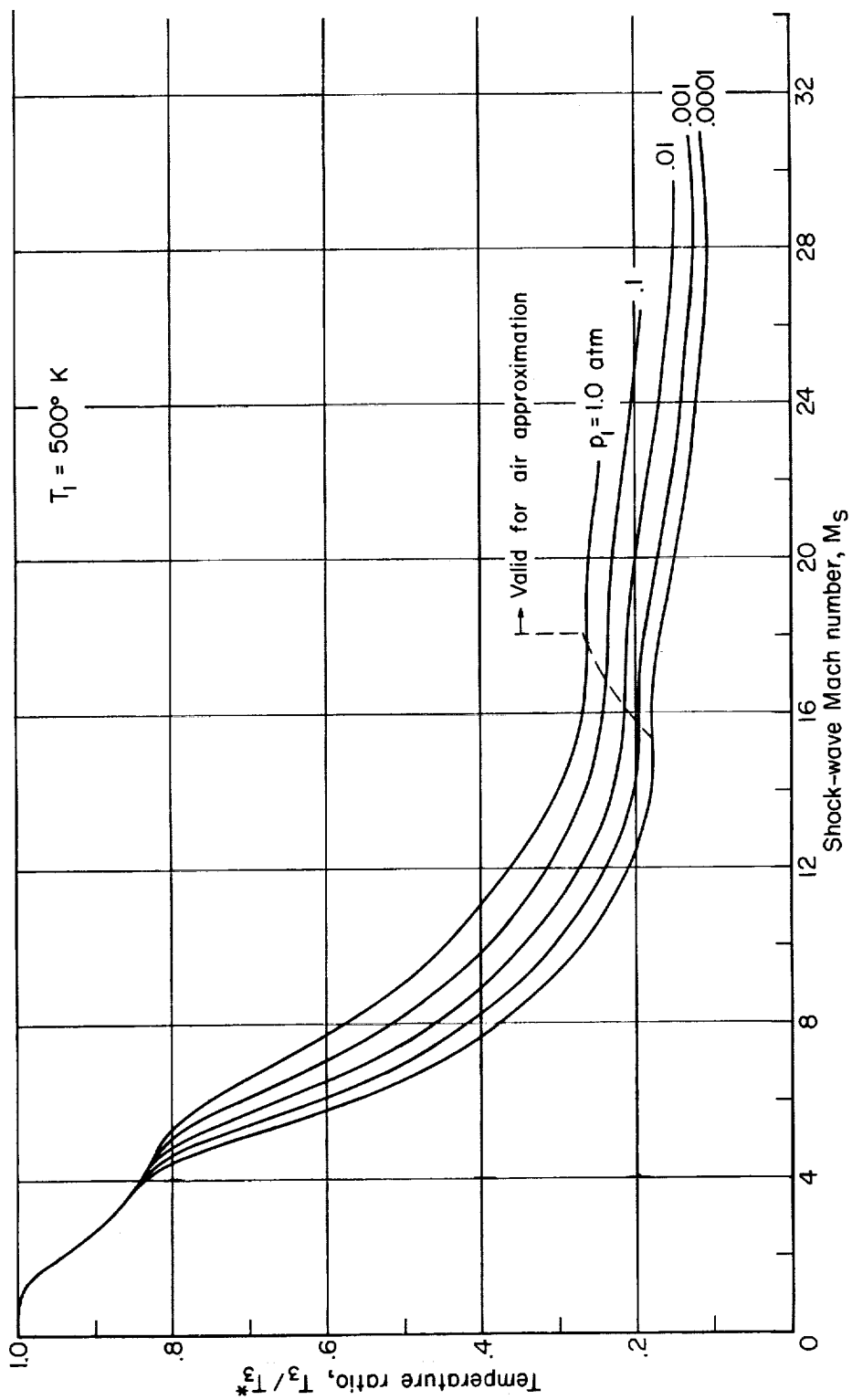
(g) Temperature ratio behind reflected shock.

Figure 19.- Continued.
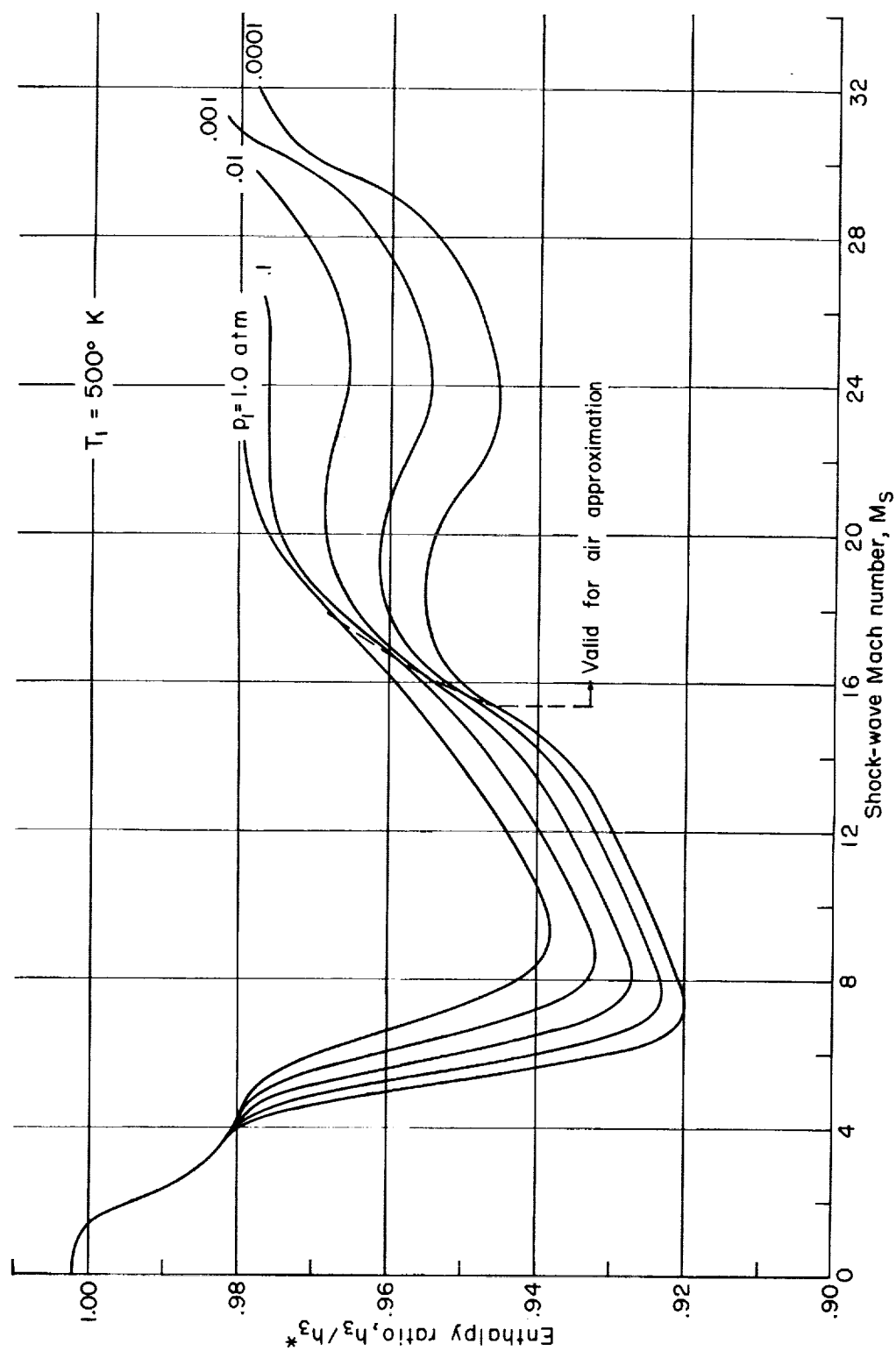
(h) Enthalpy ratio behind reflected shock.

Figure 19.- Concluded.
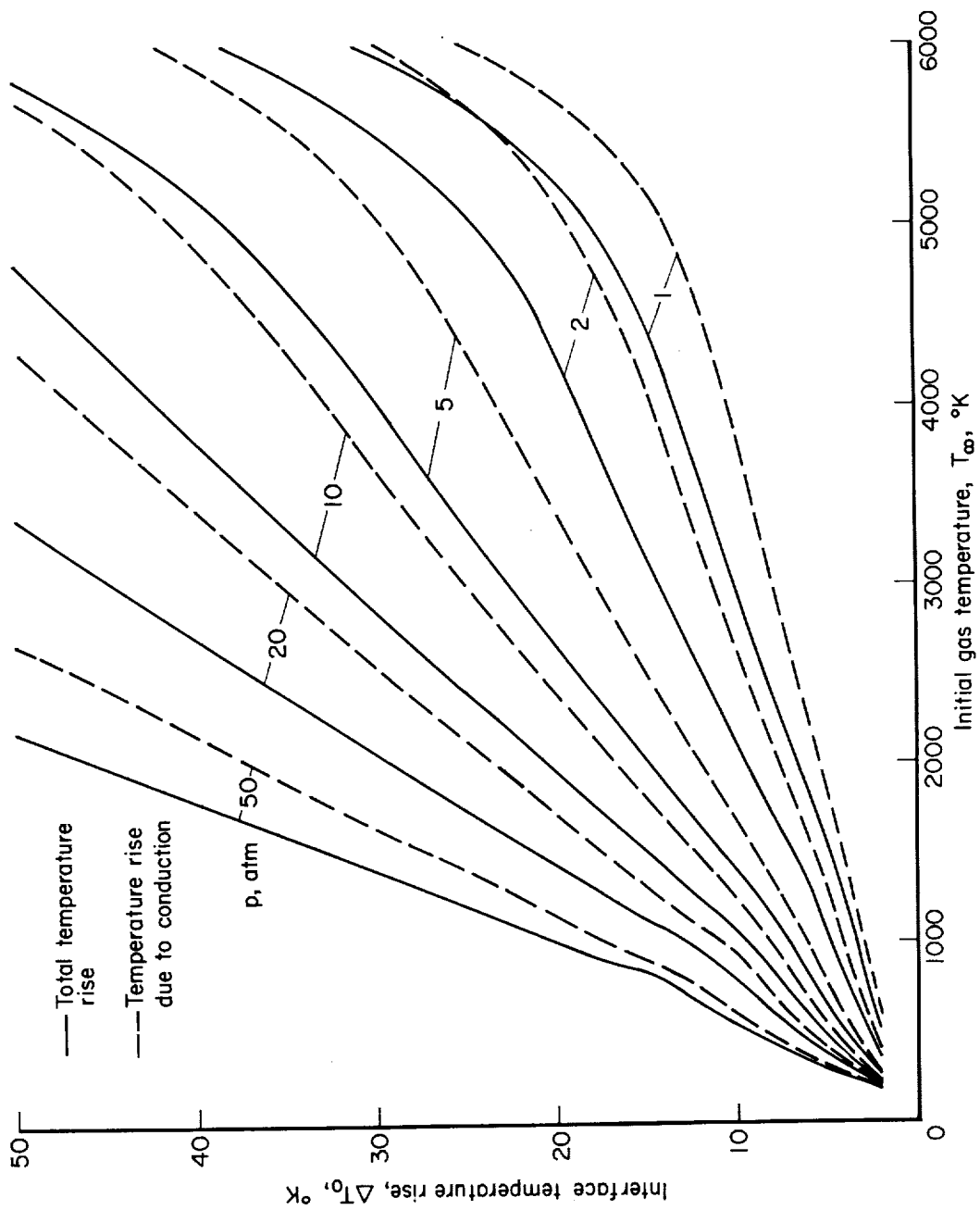
Figure 20.- Theoretical estimates for the interface temperature rise for nitrogen shock-tube experiments.
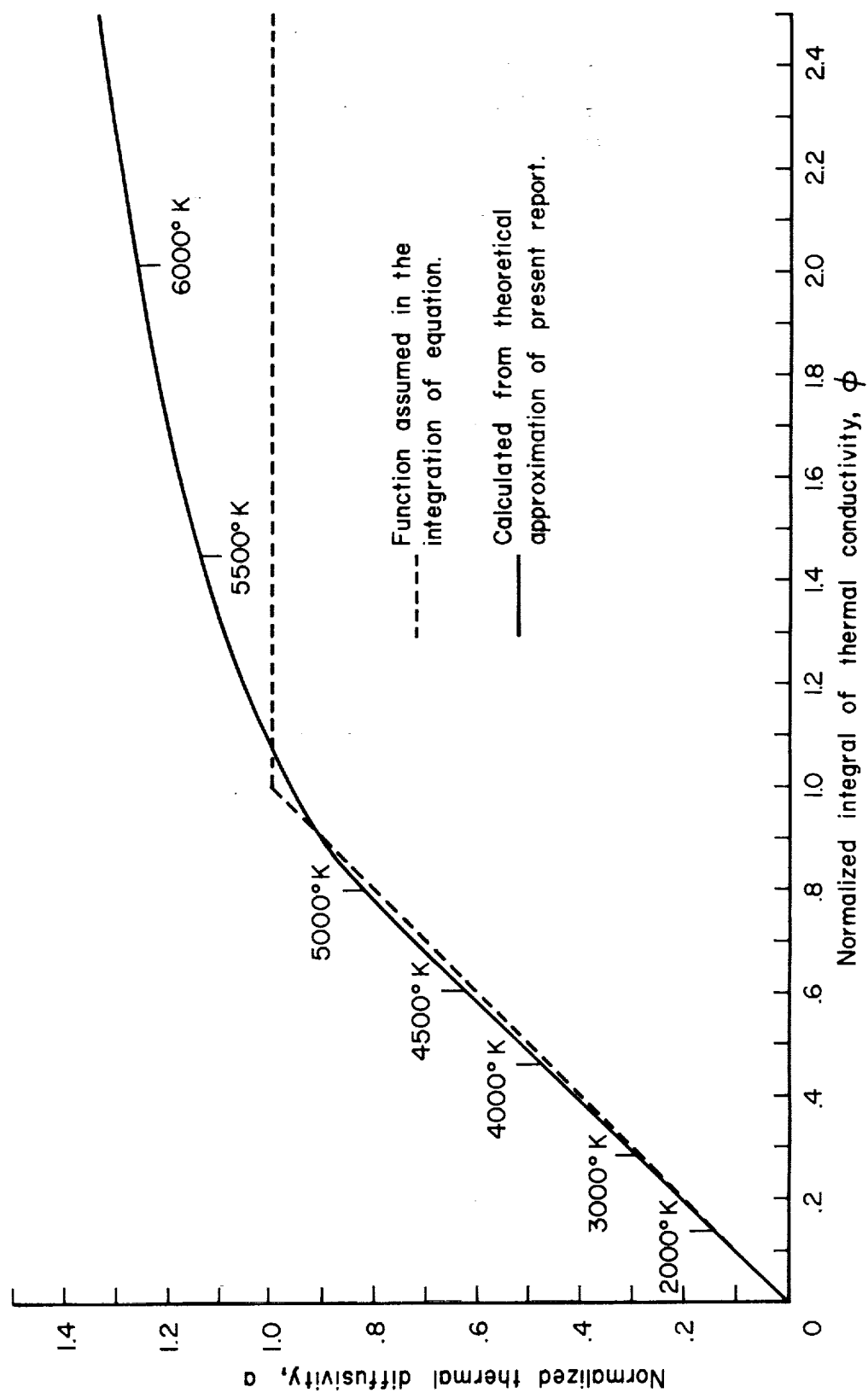
Figure 21.- Nitrogen diffusivity as a function of the integral of thermal conductivity.
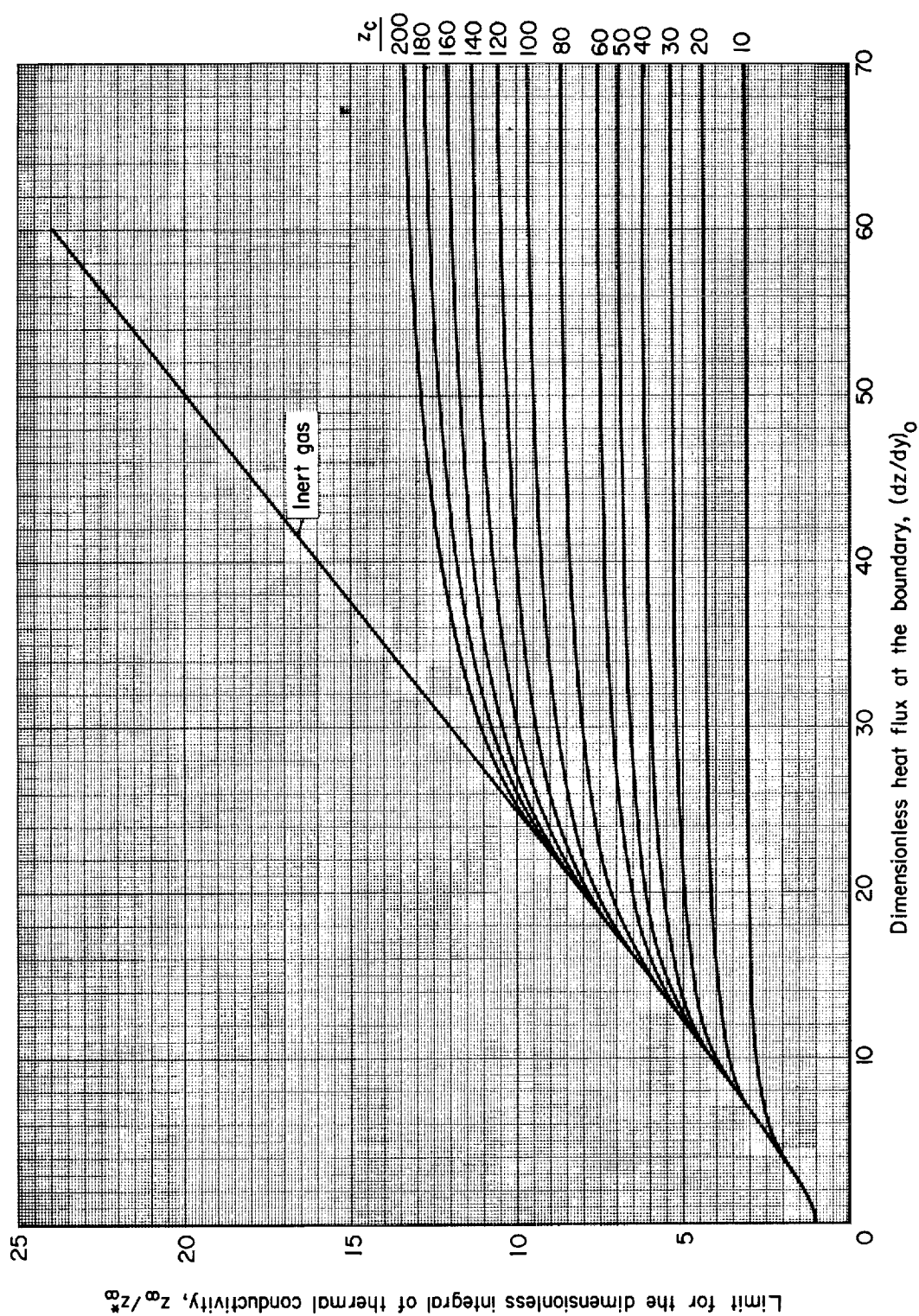
Figure 22.- Integral of thermal conductivity as a function of boundary heat flux for a reacting gas.
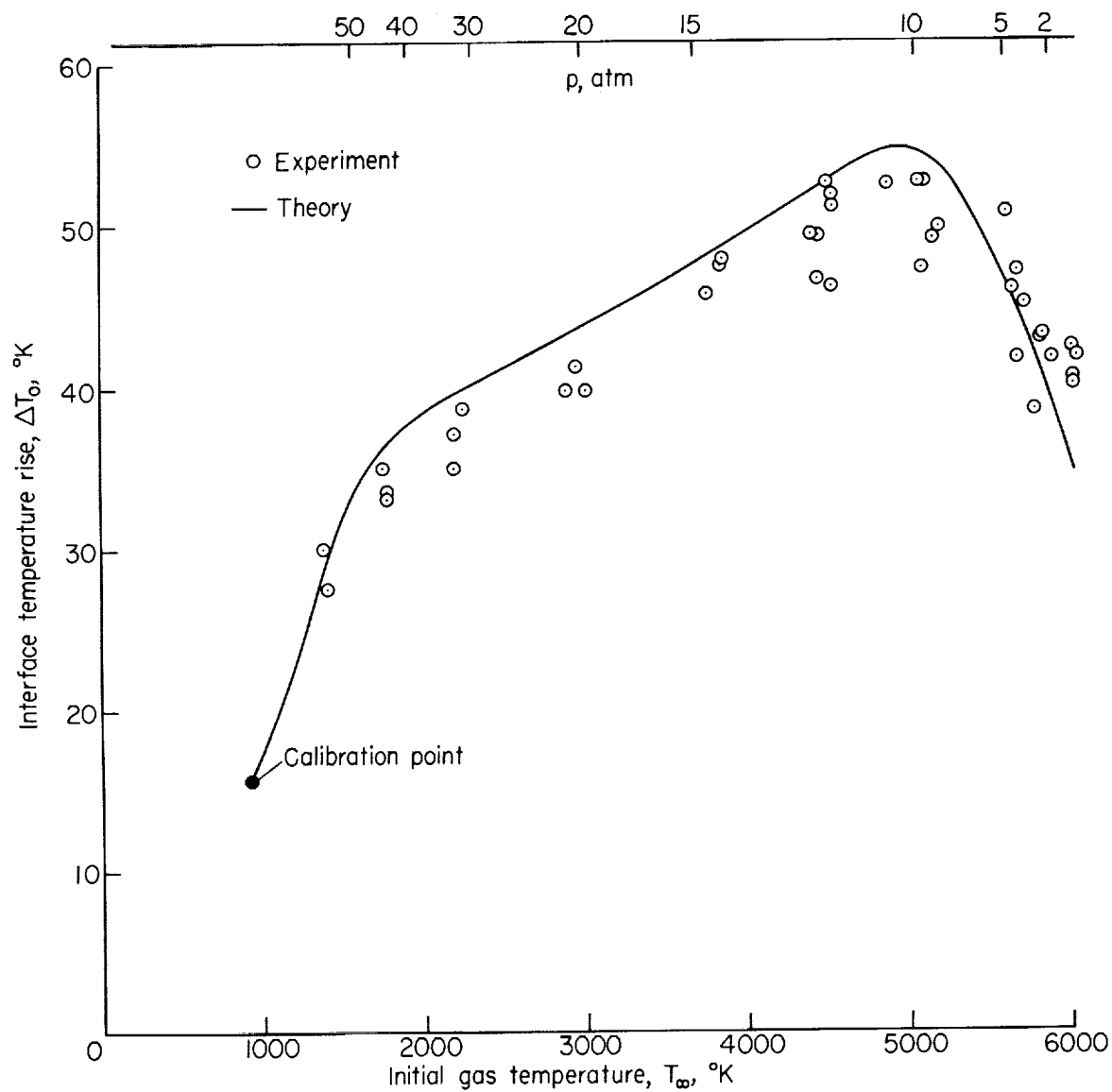
Figure 23.- Comparison of experimental and theoretical interface
temperature rise for nitrogen.

Figure 24.- Comparison of experimental and theoretical integrals of
thermal conductivity for nitrogen.

NASA TN D-1303
National Aeronautics and Space Administration.
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APPLICATIONS. Warren F. Ahtye and Tzy-Cheng
Peng. August 1962. 107p. OTS price, $2.50.
(NASA TECHNICAL NOTE D-1303)

Approximate thermodynamic and transport properties
of equilibrium nitrogen have been calculated over a
range of temperatures and pressures from 293° to
$30,000^\circ$ K and 10^{-4} to 10^3 atmospheres. Three
reactions, dissociation, single ionization, and double
ionization, have been considered. The nitrogen prop-
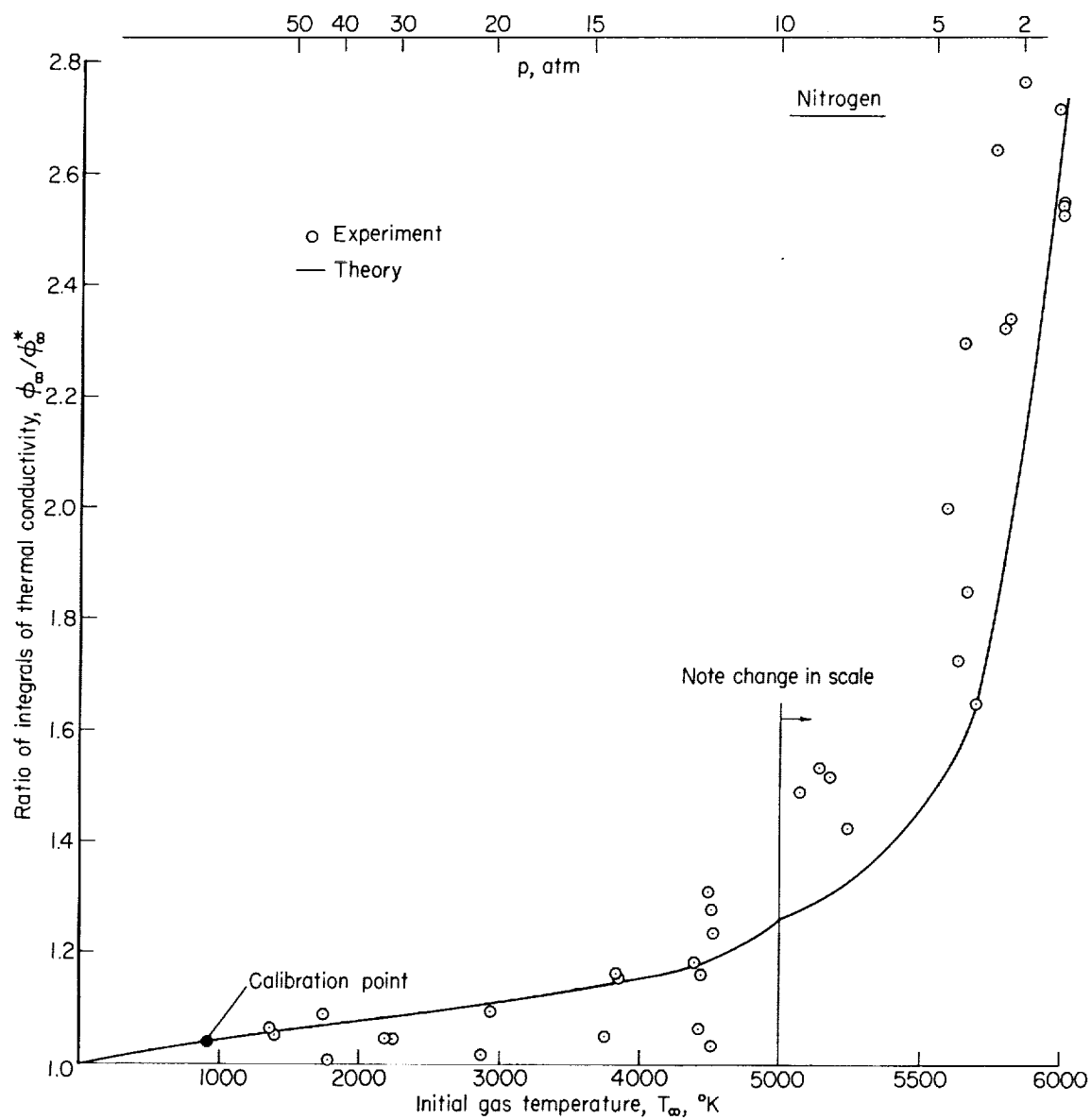erties were found usable as an approximation for air
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